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United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station
Ogden, UT 84401**

Research Paper
INT-361

January 1986

Four Analytical Approaches for Integrating Land Management and Transportation Planning on Forest Lands

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ACKNOWLEDGMENTS

Numerous Forest Service offices participated in this study. Foresters, engineers, and resource specialists on the Lolo, Kootenai, and Clearwater National Forests provided the data for the approaches and selected the harvesting and road construction activities for the simulations. Although many people were involved, several individuals on each Forest played particularly key roles: Douglas Berglund, Earl Sutton, and Wayne Johnson (Lolo NF); Jerrold Park, Robert Wetzel, and Joseph Lewicki (Kootenai NF); and Maurice Pare, Ed Butler, and Richard Patten (Clearwater NF). Also, the Engineering, Timber Management, Program Planning and Budgeting, and Management Systems staffs in the Northern Region headquarters provided valuable support and guidance in the design and completion of this study. Key roles here were played by Charles Burley, Dayton Nelson, William Schnelle, and David Wright. Finally, Peter Wong and Malcolm Kirby of the Forest Service Management Science Staff at Berkeley, CA, provided valuable assistance in the operation of the Integrated Resources Planning Model software used in this study.

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RESEARCH SUMMARY

When and where to harvest timber and construct roads on a site-specific basis must be decided when implementing forest plans. Many managers believe that such decisions are best made using an integrated, area-level analysis, applied on contiguous areas 5,000 to 50,000 acres in size. This analysis would focus on the efficiency of harvesting practices and road construction patterns (location, timing, design) and environmental impacts over time.

This paper compares four "generic" analytical approaches for use in area-level analysis:

1. **Fixed-access simulation (FX).**—In the FX approach, the analyst or manager decides how each potential harvesting unit is to be accessed prior to any analysis. These routes are locked in (fixed) and cannot be altered for the rest of the analysis. Therefore, under this simulation approach, the analyst only decides which units to harvest and when the harvesting should take place.
2. **Variable-access simulation (VR).**—As in the FX approach, the analyst decides how each potential harvesting unit is to be accessed. In the VR approach, however, these routes can be changed at any time during the analysis. Therefore, the analyst chooses which units to harvest, when to harvest, and how each of those units is accessed.
3. **Simulation with minimization of road costs (MC).**—The MC approach also requires the analyst or manager to select the units to harvest and the timing of the activity. This approach then utilizes an optimization routine to determine the least cost transportation plan (sum of discounted road construction, reconstruction, haul and maintenance costs) for accessing those units.
4. **Optimization (MX).**—The MX approach simultaneously selects the combination of harvest and road construction activities which maximizes or minimizes a specified objective function while satisfying other management objectives. In this approach there are no choices for the analyst or manager to make regarding harvest or road construction activities.

Each of the approaches was tested twice (Series I and II) on three actual planning areas selected to provide a range of conditions typical of the Northern Rocky Mountains. Data, including yields, costs, and prices, as well as the site-specific harvesting and road construction activities, were furnished by cooperating National Forest System personnel. The same data were used in each approach. In each series, each approach was to identify the combination of harvest and road construction activities over a 50-year period that would result in the highest possible discounted net timber revenue (DNR) while satisfying other management objectives unique to each series (limit on sediment, water allowed by drainage, and so on). The timber harvest and road construction activities in the FX and VR approaches and harvest activities in the MC approach were selected by the National Forest System personnel.

The discounted net revenues (DNR) per acre associated with the MX approach were significantly higher (95 percent confidence level) than the DNR values associated with the other three approaches. Average DNR per acre over the three areas was $402 for MX, compared to $269 for FX, $279 for VR, and $283 for MC. No statistically significant differences were found among the other approaches. In addition, the relative increase in efficiency associated with the MX approach (as measured by the percentage of the MX DNR obtained by other approaches within a series) was consistently larger the more complex the planning problem.

Differences in harvesting and road construction patterns were not consistent between the alternatives developed via the MX approach and the other approaches. In some instances, the difference in DNR was largely explained by the fact that the MX procedure selected harvest and road construction activities, which resulted in substantially lower discounted total transportation-related costs. In other instances the MX alternatives would harvest more timber and construct more miles of road, resulting in higher discounted costs, but also higher net revenues.

An additional harvest-volume-constrained MX alternative was developed for each test area to determine the effect on DNR of restricting the MX approach to the same harvest volumes by time period as the Series II VR and MC alternatives. DNR's per acre decreased relative to the Series II MX alternatives ($40 on the average) but were still significantly greater than the Series II VR and MC alternatives (differences averaged $86 and $82 per acre, respectively).

Data preparation over the three areas averaged 5.5 person-days per 1,000 acres having harvest potential in the next 50 years. An additional half person-day was required by the MX approach. There could be major differences in speed, efficiency, and error-checking among prospective computer programs for implementing any of the approaches. Once data are entered, the MX approach requires more computer resources due to the large number of calculations. The FX, VR, and possibly the MC approaches could be accomplished using a microcomputer or minicomputer.

Four Analytical Approaches for Integrating Land Management and Transportation Planning on Forest Lands

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INTRODUCTION

The Forest and Rangeland Renewable Resources Planning Act of 1974, the National Forest Management Act of 1976, and various implementing regulations mandate that forest management plans are developed for each National Forest. The purpose of this planning process is to develop the direction of management to be applied in the future. This includes selecting management prescriptions for each land delineation. In addition, forest planning also provides scheduling objectives for timber and other resource outputs, Forest-wide for the entire planning horizon and by management area for the first one or two decades. A management area is a grouping of acres having similar management objectives and a common management prescription. In some instances, it may be possible to disaggregate timber harvest schedules into smaller land delineations.

The need for analysis will not end with the forest planning process, however. Because of the magnitude of the task of developing a long-range, integrated plan for a National Forest (often 1 to 2 million acres in size), much of the analysis in forest planning has to be conducted at a relatively low resolution. As a result, while the type of management to be implemented is rather specific, the actual activities to carry out these management prescriptions are not specified in a site-specific manner. The challenge for the next level of analysis is to identify when and where treatment activities should occur in order to efficiently implement a plan.

Many resource managers believe that area-level analysis (ALA) is the logical next step once the information from a forest plan is extracted in as much detail as is practical and warranted. ALA is envisioned as an interdisciplinary process concerned with the management of geographically contiguous land areas from 5,000 to 50,000 acres in size. Specifically, it would concentrate on economic efficiency with regard to:

1. The location and timing of timber harvesting, road construction, and other land management activities.
2. Operational alternatives not previously specified in a forest plan, including analyzing such things as alternative silvicultural systems, logging systems, and road standards.
3. Cumulative environmental effects over time, including prediction of sedimentation and water yields in specific drainages or portions of drainages, the effect of harvesting and road construction on big game habitat, and so on.

The end result of ALA would be an operational plan for managing an area over, say, a 50-year period. Such a plan would identify the location and timing of timber harvest, road construction, and other management activities that are judged to be the most effective way to implement the forest plan in that area. This plan then provides specific direction for the projects to be conducted in an area.

The analytical approaches that could be used to conduct ALA range from "seat-of-the-pants" professional judgment, to computer-aided simulation approaches, to rather sophisticated optimization techniques. For most planning areas there would appear to be a large number of potential combinations of activities and timing sequences that could be used to implement forest plans. In addition, a number of pieces of information are necessary for developing and evaluating alternatives (timber volumes at various times, costs of various activities, sediment yields over time resulting from certain combinations of management activities, and so on).

Given the complexities of ALA, the advantages of some sort of computer-aided analysis seem apparent. The choice, it would seem, should be based on the following two questions. First, what differences in efficiency can be expected among the potential approaches? Second, what differences exist in terms of the resources required to conduct the potential approaches?

This report presents the results of a study that addressed these questions. The study tested four analytical approaches on three actual planning areas. These included two simulation approaches that vary by the flexibility allowed the user in selection of road access routes; a combination of simulation and optimization where the analyst makes harvesting and other land management choices and then uses an optimization procedure to minimize the road-related costs for accessing those activities; and an optimization procedure that selects both the land management activities and road construction alternatives, based on a user-supplied objective function to be maximized or minimized, and user-supplied management constraints to be satisfied.

The paper is organized as follows. First, we discuss the basic formulation for ALA used in all four approaches (land and road network delineations, costs to be included, and so on). Then, we describe in more detail each of the four approaches. This section is followed by the study methods—experimental design, how each approach was applied, and so on. Finally, we present the results of the comparisons and our conclusions.

DEVELOPING A BASIC FORMULATION FOR ALA

Delineating Land Area

Each area was delineated into potential harvesting units, based on logging, site preparation, and regeneration considerations. Figure 1 illustrates the units established for the Twin Rocks area, one of the three test areas in the study.

Many strategies were available for delineating land, for example, categorizing by vegetation, site productivity, or topographical features. The potential harvesting unit strategy was selected because it provides the spatial orientation needed for ALA. This approach ensures that members of an interdisciplinary team have the same image of proposed alternatives. This cannot be accomplished when harvest alternatives are formulated in terms of percentages of land categories to be harvested. In addition, harvest alternatives need to be geographically specific if transportation strategies are to be analyzed in sufficient detail.

Timber Management Projects

Timber management projects that implement the management objectives specified in the forest plan were developed for each of the potential harvesting units. A given project includes a schedule of activities (such as sale preparation, timber harvest, site preparation, and regeneration) to be applied on a potential harvesting unit. Alternative timings for activities were handled by developing alternative projects with different timings. In some instances a forest plan prescription may allow for operational alternatives, such as silvicultural system or logging method. These alternatives are included by developing timber management projects for each option.

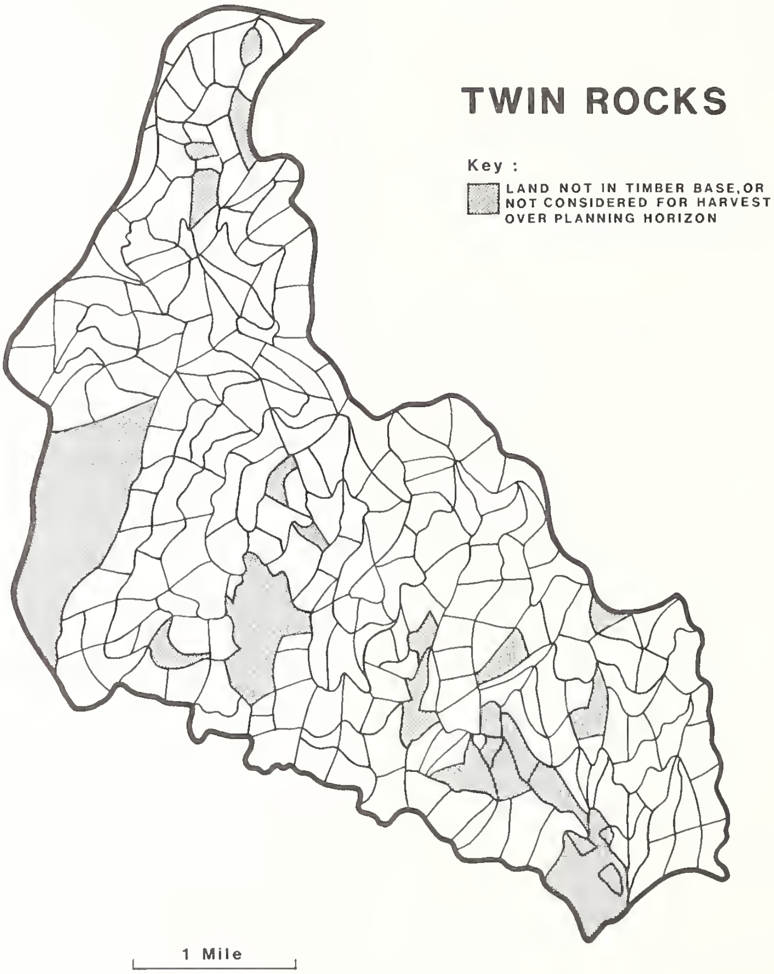

TWIN ROCKS
Key :
▨ LAND NOT IN TIMBER BASE, OR NOT CONSIDERED FOR HARVEST OVER PLANNING HORIZON
1 Mile

Figure 1.—Potential harvest units for Twin Rocks.

Potential Transportation Network

The transportation portion of ALA is based on a potential transportation network. This network must be compatible with the potential harvesting units and logging methods, as well as the expected kinds and amounts of traffic. At this point, a reasonable number of routes should be included to provide alternative access routes to potential harvest units and groups of units.

Once developed, a potential network is delineated into "links," which are bounded by "nodes." This concept is illustrated in figure 2, which presents the network for the Twin Rocks test area.

Road Construction Projects

Road construction (or reconstruction) projects were developed for the links representing proposed roads or existing roads requiring reconstruction. The projects for a given link vary primarily by the timing of the construction or reconstruction. In addition, road standard alternatives were included for a link when it was not clear prior to an analysis what standard is most appropriate. When a potential road network includes more access routes than necessary (to provide alternative transportation strategies), some of the links would not be selected for construction in a given alternative.

Analysis Approaches Tested

The study tested four computerized analytical approaches for use in ALA. These were: (1) fixed-access simulation (FX), (2) variable-access simulation (VR), (3) simulation with minimization of transportation-related cost (MC), and (4) optimization (MX). It is appropriate to think of these approaches as "generic" categories. That is, we were testing approaches, **not** computer software. Several software systems exist that could accomplish parts or all of several of these approaches, and any number of new systems could be developed.

Each of the four approaches is based on the formulation just described. Therefore, the first step in each approach is to develop the potential harvest units, the timber management projects, the potential transportation network, and the links and road construction projects.

Fixed-Access Simulation (FX).—In the FX approach, the analyst must choose among the timber management projects and road construction projects. A computer simulation program is used only to aid in calculating useful information for evaluating area plans. This approach represents a rather simplistic simulation design. After development of the potential harvest units, road links, and associated management and construction options, the analyst identifies the road links that access

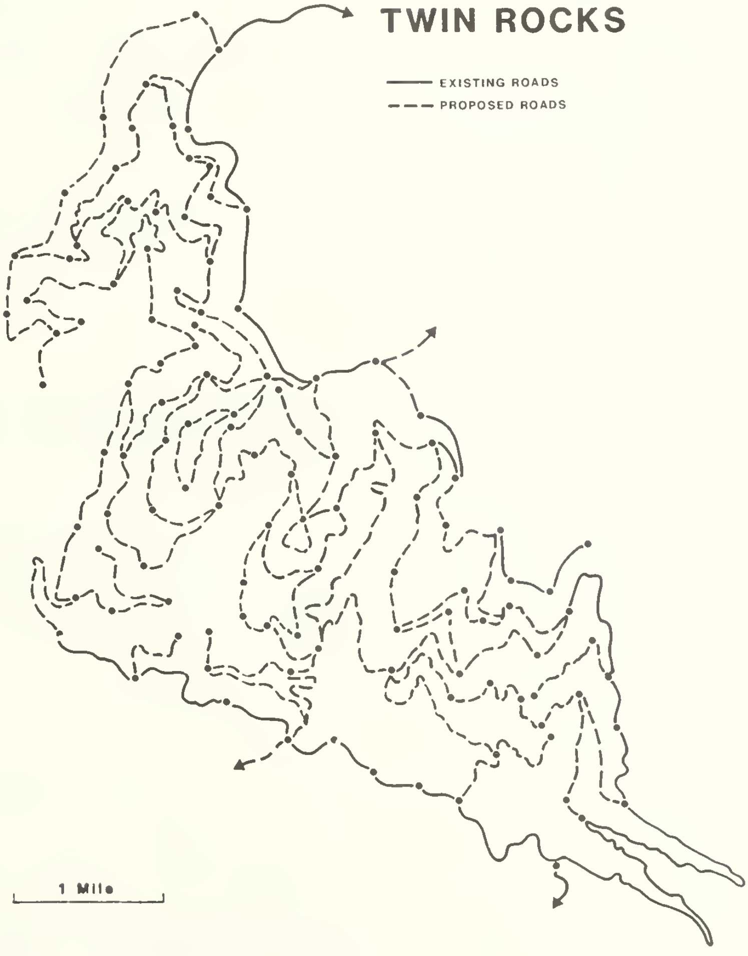


Figure 2.—Potential road network for Twin Rocks.

each potential harvest unit. This transportation strategy is then locked in (**fixed**) for the remainder of an analysis.

Next, the analyst chooses among the timber management projects developed for the potential harvest units. These selections are entered into the program, which determines (from the fixed transportation strategy developed earlier) the links to be constructed by time period and road standard to access the units selected for treatment. The program then calculates information for evaluating the management alternative entered for the area. This includes such things as discounted net timber revenue, net timber revenue by time period, costs by several categories, sediment by drainage and time period, and so on. The analyst then studies the results, makes desired modifications in the selection of land management projects, and runs the simulation program again. It may take numerous "runs" to develop an alternative for an area that is judged to be desirable.

Variable-Access Simulation (VR).—The VR approach is more sophisticated than the FX approach in that the analyst is given the opportunity to modify the choice of road links that access potential harvest units between simulation runs.

This approach also begins with an analyst-specified transportation strategy. Here, however, it is only tentative and used primarily for calculating information that aids in the selection of resource and road construction projects (timber revenue net of haul and other costs, construction costs, sediment per project, and so on). The analyst then makes the initial selections of resource and road projects and enters them into the computer. Road projects could be entered as a list, or as modifications from the tentative transportation strategy entered earlier. The program then calculates the results of the selections as in the FX approach (discounted net timber revenue, costs, sediment by drainage, and time period, and so on). The analyst then makes any desired modifications, including changes in either resource or road projects, and runs the simulation program again. This process is repeated until a satisfactory alternative is developed. The simulation program PASS (USDA Forest Service 1985) fits into the variable-access simulation category.

Simulation with Minimization of Road Cost (MC).—The MC approach combines a simulation approach for land management activities with a cost minimization routine for selecting road construction projects. The resource projects are selected by the analyst and entered into a computer system, as in the first two approaches. Such a system, however, then utilizes a network optimization routine to select the combination of road construction projects that provides access for the selected land management activities at the least overall transportation-related cost. This cost is defined as the sum of haul, maintenance, road construction, and reconstruction costs expressed in present value (discounted) terms. Once the selection of road projects has been made, the computer program calculates the same type of information for evaluating the alternatives as the simulation approaches (discounted net timber revenue, costs, sediment by drainage, and time period). The analyst has the option of modifying the selection of resource projects and repeating the process.

Several examples of cost-minimizing network models that might be used in the MC approach include: MINCOST (Schnelle 1977), the Timber Transport Model (Sullivan and Barnes 1980), TRANSHIP (Kirby and others 1981a), and NET4T (Sessions 1985).

Optimization (MX).—In the MX approach, a computerized optimization model selects the combination of timber management projects and road construction projects that maximize or minimize some objective and satisfy specified management constraints. The analyst must specify an objective function to be maximized (or minimized). We envision that maximizing discounted net revenue (DNR) would be frequently used in ALA, although other objective functions could be used as well; for example, minimizing discounted total cost, maximizing timber volume, or minimizing quantity of sediment. In addition, the analyst has the option of including management objectives that cannot easily be reflected in an objective function as constraints to be satisfied. This could include such things as sediment or water yield for which it is difficult (or impossible) to estimate dollar values.

Once the objective function and constraints have been specified, the solution is found that identifies the combination of resource and road construction projects that maximizes (or minimizes) the specified objective function while satisfying the constraints. In addition, the model calculates (based on the selection of resource and road projects) the same type of information for evaluating the alternatives as the first three approaches. The analyst then has the option of modifying the constraints or selecting a different objective function and reoptimizing the model.

The Integrated Resource Planning Model (IRPM) (Kirby and others 1981b) and a test release of FORPLAN Version II (Johnson 1985) are two examples of existing computer systems that could potentially be used to conduct this type of optimization analysis.

TESTING ANALYTICAL APPROACHES

Test Areas

The four analytical approaches were tested on three areas. The objective in selecting the three test areas was to provide a range of conditions over which to compare the four approaches. One area was to be small in size, with a planning problem of no more than moderate complexity; a second area was to be of moderate size and complexity; and the third area, large, with a relatively complex planning problem. It was hypothesized that complexity in planning is affected by such factors as the distribution of merchantable timber coupled with topography; environmental, and other nontimber objectives; and the shape of the proposed transportation network. In reality, the choice of test areas was limited by the number of Forest Service District offices that expressed interest in cooperating in the study and by the areas offered for analysis.

The three test areas chosen (location shown in fig. 3) are described below:

Twin Rocks Area (fig. 1)

—Lolo National Forest

—6,400 acres (total)

—5,950 acres with harvest alternatives in the 50-year planning horizon

—About 10 percent of area is currently accessible by existing roads not requiring reconstruction.

—Virtually no harvesting has been done in area in the past.

—The road network is best described as a "grid" network in that there are a number of potential connecting roads (fig. 2).

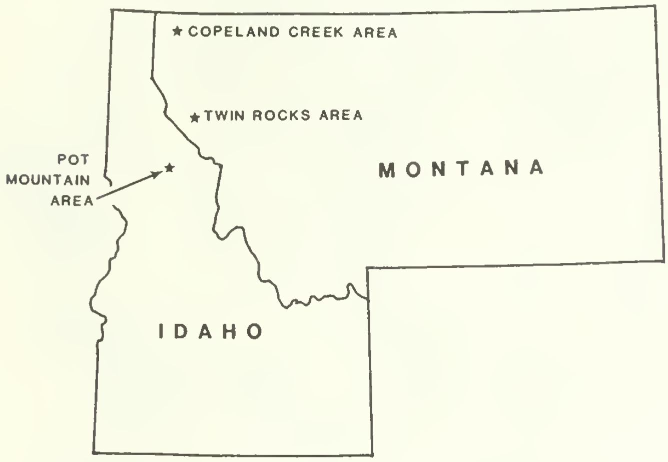


Figure 3.—Location of test areas.

Copeland Creek Area (fig. 4)

—Kootenai National Forest

—16,870 acres (total)

—8,640 acres with harvest alternatives in the 50-year planning horizon

—About 40 percent of area is currently accessible by existing roads requiring no reconstruction.

—There are a number of harvest units from previous sales in early stages of regeneration in area.

—The road network is best described as two trees placed top-to-top with a few connecting branches (fig. 5).

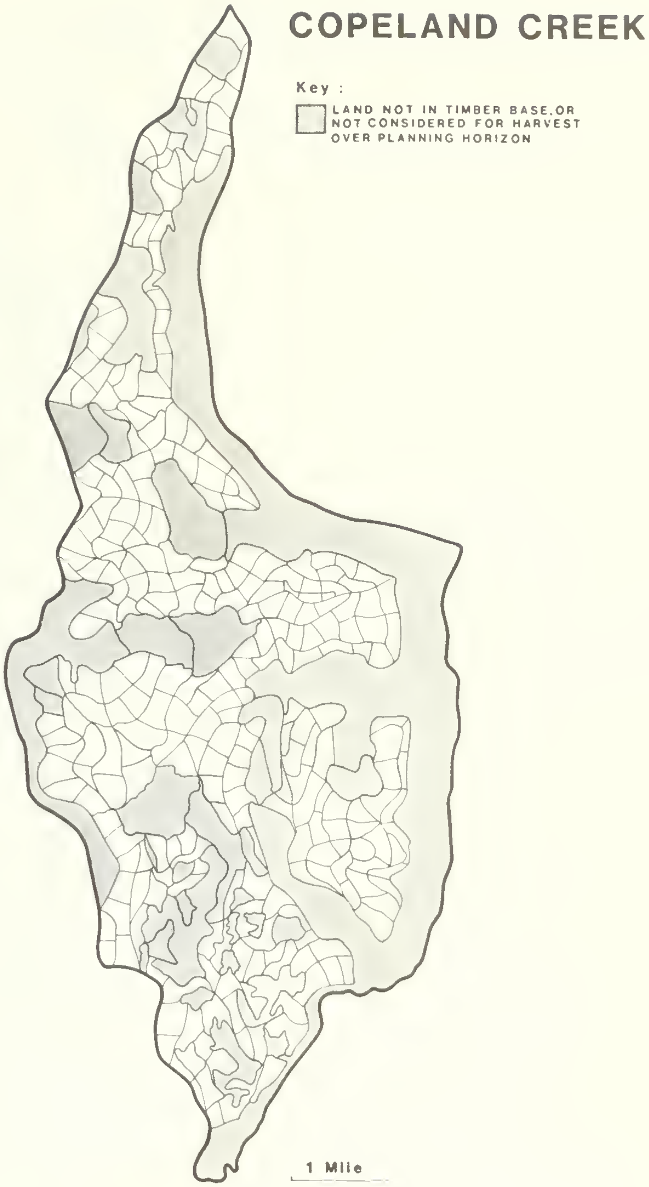

COPELAND CREEK
Key :
LAND NOT IN TIMBER BASE,OR NOT CONSIDERED FOR HARVEST OVER PLANNING HORIZON
1 Mile

Figure 4.—Potential harvest units for Copeland Creek.

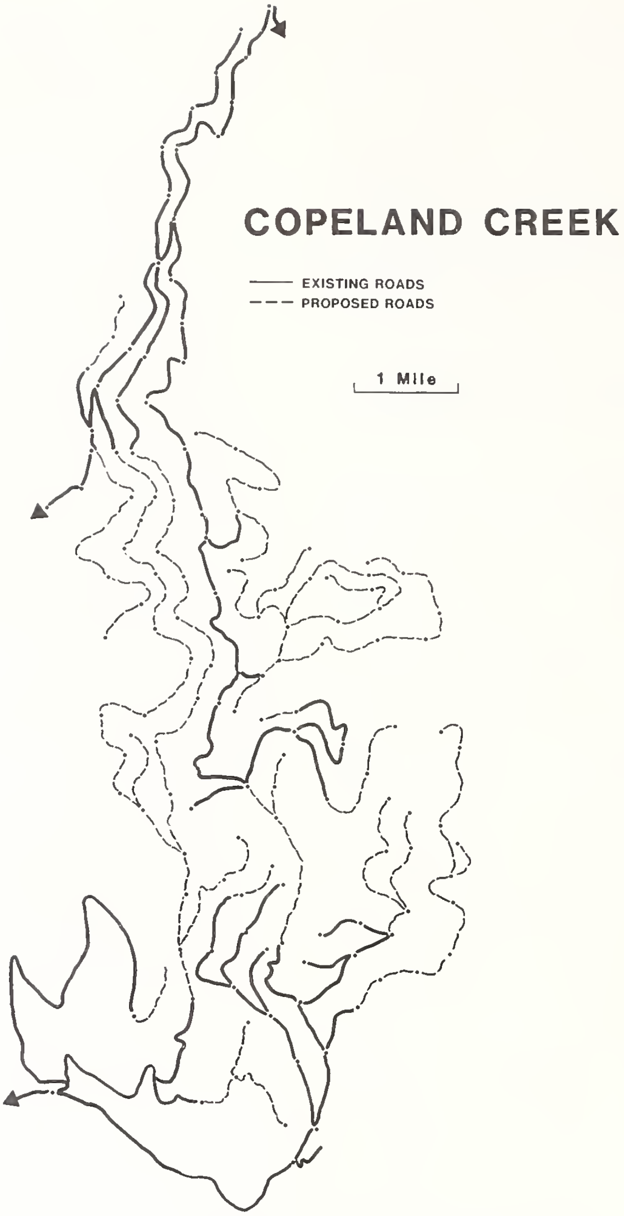


Figure 5.—Potential road network for Copeland Creek.

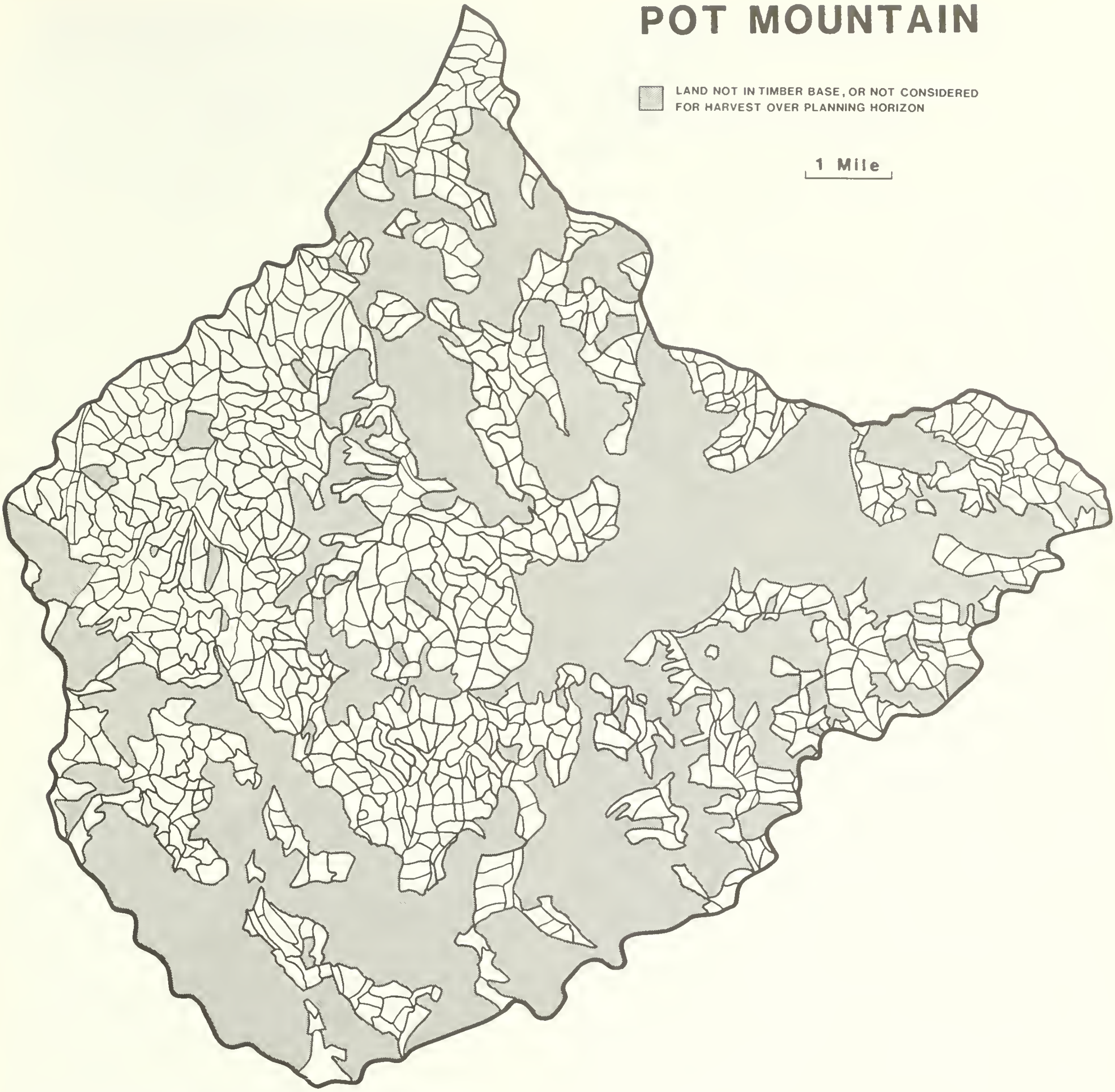

POT MOUNTAIN
▨ LAND NOT IN TIMBER BASE, OR NOT CONSIDERED FOR HARVEST OVER PLANNING HORIZON
1 Mile

Figure 6.—Potential harvest units for Pot Mountain.

Pot Mountain Area (fig. 6)

- —Clearwater National Forest
- —51,870 acres (total)
- —25,950 acres with harvest alternatives in the 50-year planning horizon
- —About 5 percent of area is currently accessible by existing roads not requiring reconstruction.
- —Essentially no harvesting has occurred in the area in the past.
- —The road network has a main loop through the area, a smaller loop off the main loop, and a number of smaller tree-shaped networks feeding into these loops (fig.7).

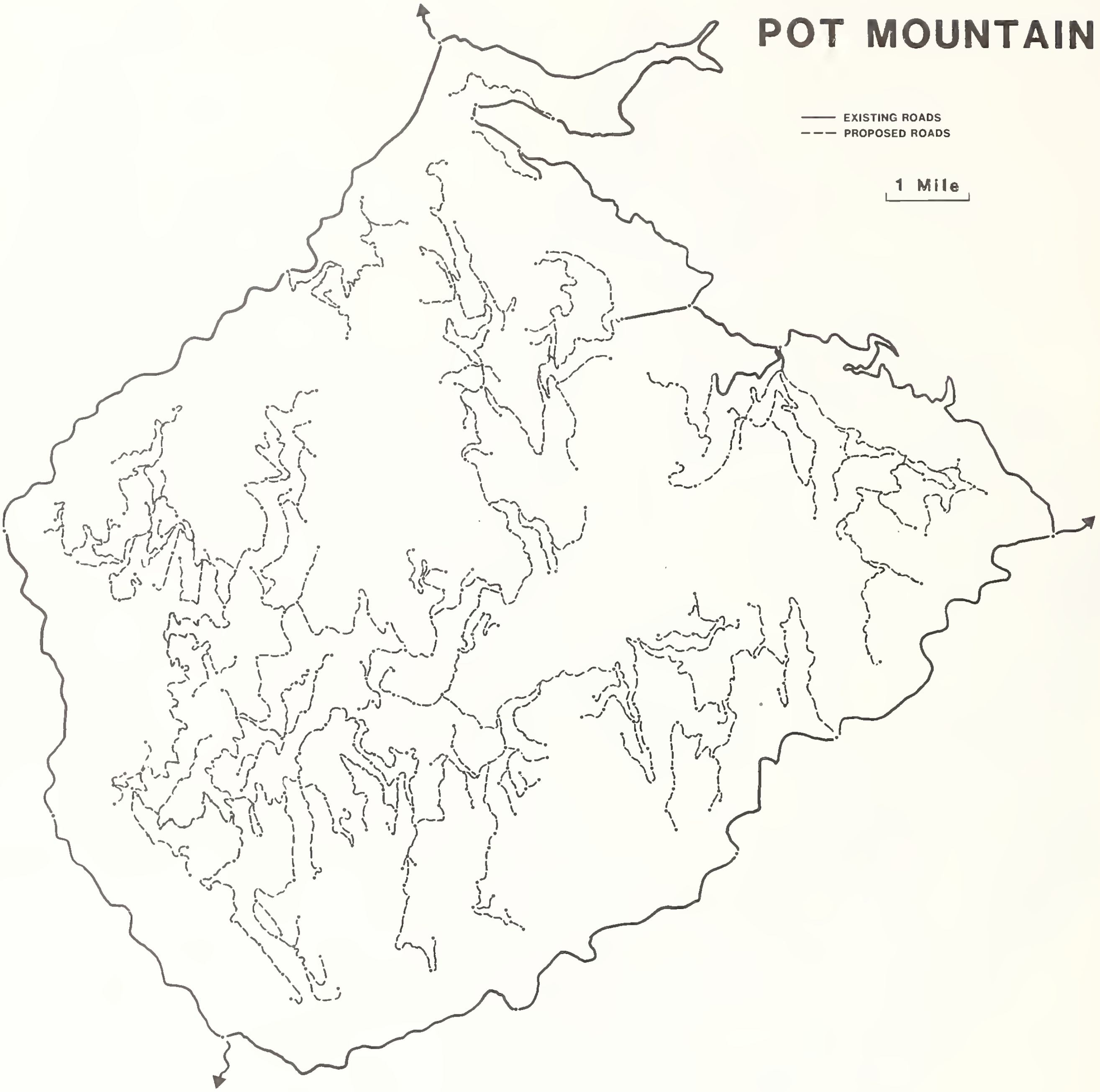


Figure 7.—Potential road network for Pot Mountain.

Summary of Data Used

Data for the test areas were furnished by the cooperating District and Forest personnel. In addition, whenever professional or managerial judgments were required (such as location of roads and potential harvesting units), those judgments were made by National Forest System personnel. The following discussion summarizes the various categories of data used.

Potential Harvest Unit Delineations and Resource Projects.—The land within each test area was delineated into potential harvest units, as described earlier under Developing the Basic Formulation for ALA. The criteria used for delineation were that the units be consistent with the type of management identified for the area and that the units represent what appears to be an efficient design with regard to logging method and road location. Units varied in size, with the largest being about 40 acres.

Timber management projects, which identified packages of land management and timber harvest activities, were developed for each potential cutting unit. Each project included all the activities that occur from sale preparation to regeneration of the site. Composition of the projects followed the type of management to be applied, as identified in forest planning. Therefore, the projects for a given unit differed primarily by the timing of activities. Choice of silvicultural system was also an option for about a third of the cutting units whenever more than one approach to cutting unit management was possible and yet consistent with the forest plan. Finally, there was a choice between skyline and helicopter logging systems for a few units.

Transportation Network and Road Construction Projects.—Potential transportation networks were developed for each area (figs. 2, 5, and 7). These networks are operationally viable (potential roads can be built within a horizontal tolerance of about ±100 feet) and compatible with the type of management and logging systems identified for the area. The networks were delineated into links in a manner that provided a reasonable amount of analytical detail (the amount links overshoot or undershoot access to units was kept to a minimal level) yet held the number of links to an amount which can be handled efficiently in an analysis.

Construction projects were then developed for the links representing proposed new roads and for links representing existing roads that require some reconstruction. The road alternatives developed for each link varied by the time period in which construction would occur and, for some links, by road standard. The road project costs included road design and layout as well as the construction itself.

Time Periods.—This study adopted a 50-year planning horizon composed of the following time periods:

Time period	Decades
1	1
2	2
3	3-5

This choice of time periods resulted from a compromise of three objectives: (1) the first two time periods should sum to no more than 20 years so that a fair amount of time specificity can be maintained in the early portion of the planning horizon, (2) the time periods should provide ability to analyze trade-offs between conducting specific activities in the near future versus the more distant future, and (3) the number of time periods should be held to a minimum to keep the analysis as simple as possible.

Yield Information.—Five types of physical yield information were included for the three test areas, although only timber yields were present in each of the three areas. Timber yields for each potential harvesting unit were projected to the midpoints of each time period. Because the potential harvesting units were site-specific, yield projections were based on the most specific timber data available.

Two of the yield categories measured big game forage production: thousands of pounds, dry weight and acreage in forage-production. The latter was used in calculating cover/forage ratios and for constraining these ratios between specified lower and upper limits. Both measures of big game forage production were tied to the type of harvest. Predicted increases in forage production due to harvesting (which typically peaks within 20 to 30 years after harvest and then decreases as trees become reestablished) were projected from the time of disturbance through the planning horizon. Both were measured in terms of annual average quantity per decade.

The remaining two yield categories, water and sediment yields, were included to assess environmental impacts. Water yields were tied to timber harvest activities and sediment to road construction and harvest activities. Water and sediment increases (which generally peak within 10 years after disturbance and then decrease as the disturbed area becomes revegetated) were projected from time of disturbance through the planning horizon. Both were measured as an annual average quantity per decade.

Economic Information.—Timber was the only output valued in dollars. The basis for timber prices was mill-delivered logs. Species categories were used to handle variations in unit value. Costs included all purchaser costs for harvesting, haul and road maintenance, and contract-related costs such as slash disposal. Forest Service costs included road construction (regardless of method of financing), road design and layout, brush disposal and regeneration of timber, sale preparation and administration, and postsale silvicultural exams. Agency costs that do not vary as a result of these activities (Regional Office and Washington Office overhead costs) were not included.

All timber prices and costs were expressed in 1982 dollars. Assumptions about real changes in prices and costs were the same as those used in the respective forest planning processes. A real dollar discount rate of 4 percent was used.

There were several reasons for valuing timber as delivered logs and including purchaser costs (rather than using stumpage prices). Forest Service design of road networks and timber sales can affect purchaser costs, which in turn are counted against the price of stumpage. Road network design affects haul costs and road construction costs. Timber sale design affects stump-to-truck costs, purchaser slash disposal costs, and other costs associated with specifications in timber sale contracts. Any cost the Forest Service imposes on a purchaser can be expected, on the average, to be subtracted from the amount the Forest Service receives for the timber sold. Thus purchaser costs can be expected to have the same effect on DNR for the Forest Service as costs incurred directly by the Forest Service.

Valuing timber as delivered logs and subtracting both purchaser costs and Forest Service costs has two advantages over the alternative of valuing the timber—such as would be done using a transactions evidence approach based on stumpage price. First, haul cost can be handled explicitly in the transportation analysis conducted in ALA. In some instances there are trade-offs to be made between higher haul costs and lower road construction costs and vice versa. In contrast, haul cost is implied (imbedded) in stumpage price. Therefore, the only transportation analysis that can be accomplished in ALA when stumpage price is used directly to value timber involves minimizing road construction cost. Any trade-offs between haul cost and construction cost cannot be addressed. Second, valuing timber as delivered logs allows for explicitly identifying and treating other cost components (for example, stump-to-truck costs, purchaser slash disposal costs) that are "hidden" in stumpage price values.

Comparing Approaches

Each approach was applied twice (Series I and Series II) on each area. The objective for Series I was to develop an area plan with discounted net revenue (DNR) as large as possible, while satisfying the adjacency rule. This rule states that, if a unit is harvested, an adjacent unit cannot be harvested for at least two decades. This is roughly the amount of time it takes to regenerate and grow the new stand of trees to a size such that the unit again appears forested and no longer is considered an "opening." This rule, along with the size limitations on the potential harvest units themselves, maintains harvest openings to a size consistent with Forest Service policy. The intent of Series I was to develop a baseline alternative that shows the largest net timber revenue that could be obtained over the planning horizon, with only very minimal environmental restrictions.

For Series II, the objective was to develop a plan with DNR as large as possible while achieving environmental objectives and meeting the adjacency rule (see table 1). The Series II plans represent packages of activities that are consistent with the management approach selected in the forest planning process.

Additional series could also have been developed with somewhat different objectives, yet consistent with forest plan direction. For example, a Series III might have included a harvest volume objective. Time and budget considerations did not permit the development of additional series.

DNR is a measure of the net effect area management has on the overall financial receipts experienced by the Forest Service, expressed in discounted dollars. It contains the following value and cost components:

Start: $ Log value (mill-delivered)
(+) Bid premium
(−) Haul and maintenance costs
(−) Purchaser slash disposal costs
(−) Logging costs
(−) Profit and risk margin
= $ Stumpage price (≅ "high bid")
(−) Road costs or purchaser road credits
(−) Site improvement, regeneration, and brush disposal costs
= $ Indicated net stumpage value
(−) Sale preparation cost (including specialists)
(−) Sale administration cost
(−) Silvicultural examination cost
End: = $ Net revenue for Forest Service

DNR was chosen as the objective that each of the approaches would attempt to maximize because it provides a good measure of long-run timber management efficiency. Any alternative that maximizes DNR and simultaneously satisfies other resource objectives is efficient. Any number of efficient plans could be developed, each with a somewhat different mix of outputs. It is the responsibility of the resource manager to evaluate which plan is preferred. In this study, DNR comparisons reflect the effectiveness of each analytical approach in developing efficient management plans.

One could alternatively attempt to maximize (or minimize) other objectives (for example, minimize overall cost or maximize timber volume). It is believed, however, that using other objectives would not affect the comparisons among the analytical approaches. That is, the approach that gives rise to the highest DNR would also give rise to the highest value regardless of the objective to be maximized, or to the lowest value for any objective to be minimized.

Modeling Procedures

An optimization model was built for each area using the Integrated Resource Planning Model (IRPM) (Kirby and others 1981b) available at the USDA Fort Collins Computer Center. These models were used for each of the four analytical approaches. For the simulation approaches, the harvesting and road construction alternatives selected for implementation were forced into solution via equality constraints. Thus, for these approaches the optimization models were run as if they were simulation models, because no choice remained regarding selection of harvest or road construction projects.

Using the same model for all four approaches ensured that exactly the same information (costs, prices, yields) was used in each. Second, it alleviated the need for developing necessary software for conducting the simulation approaches.

Description of IRPM Models.—IRPM is a mathematical modeling system in the general class of analysis known as mixed-integer linear programming. Three categories of variables are used in these models: (1) timber management projects, (2) road construction projects, and (3) traffic variables.

The timber management projects represent the harvesting alternatives for the potential harvest units. As described earlier, a timber management project includes all the on-site activities associated with harvesting and regenerating a potential harvest unit. The only costs not included in the coefficients for these projects are the haul and maintenance costs and road construction and reconstruction costs. The timber management projects were allowed to assume any value between 0 (don't do project) and 1.0 (do project in its entirety). Fractional values measure the portion of a project selected for implementation. In actuality, the majority of projects selected (above 80 percent in most cases) were entire projects.

The road construction projects represent the construction and reconstruction alternatives for the links in the road networks. Road projects were limited to values of 0 (don't do project) and 1.0 (do project). If fractional values were to be permitted, the transportation network would be discontinuous, which would be nonsensical. Road construction projects contribute road construction cost to the DNR calculations.

The third type of variables, traffic variables, was formulated as ordinary continuous variables (which can assume any nonnegative value). They measure the quantity of traffic flowing over each link by time period and road standard. Traffic variables contribute haul and maintenance cost to the DNR calculations.

The other main component of IRPM models is the constraints, which fall into two categories. The first category is the constraints that are required for the model to operate properly. These include: (1) constraints that limit to one the number of resource projects that can be simultaneously allocated on a cutting unit, (2) constraints on road project variables that ensure access for resource projects, (3) constraints that "connect" the traffic variables so they correctly measure the volume of traffic flowing over the road segments, and (4) various other constraints of similar nature. For the most part, these constraints are developed by IRPM software and will not be discussed further here.

The second category of constraints is the user-specified constraint rows. These include the management objectives listed in table 1 (which were entered as constraints), plus assorted other rows for monitoring cost categories, volume harvested by species categories, and so on. In linear programming, the user has the option of defining rows as either constraining or nonconstraining. With the exception of the constraints listed in table 1, the rows in this second category were treated as nonconstraining rows.

Fixed-Access Simulation (FX).—The first step following the development of units, resource projects, and road projects was for the cooperating National Forest System (NFS) personnel to develop the transportation plan that identified which links would be constructed to access each unit. The three transportation plans were based on analyses done using the MINCOST model (Schnelle 1977). Figure 8 presents the fixed access transportation plan developed for the Twin Rocks area.

Based on these transportation plans, the following information was calculated and supplied to the cooperating NFS personnel:

—List of discounted net revenues per acre net of haul cost for each timber management project.

—List of discounted construction costs by time period for each road link.

Given this information, the cooperating NFS personnel chose the combination of harvesting activities (resource projects) they thought would give the greatest DNR while satisfying the other objectives established for Series I and II. These selections were entered into the computer model along with the required road construction projects predetermined from the transportation plan. The model was then used to calculate total DNR, costs, sediment, and so on. The results were provided to the NFS personnel who made whatever modifications appeared necessary to either improve DNR for the area or satisfy the Series I or II objectives. The revised alternative was again run through the computer model and the results returned to the NFS personnel. This process was continued until the cooperators believed they had identified that combination of activities that would provide the highest DNR while satisfying the other objectives. The number of runs made to develop an alternative varied from one to nine.

Variable-Access Simulation (VR).—The process used for the variable-access approach was essentially the same as that described for the fixed-access approach. This approach, however, permitted the NFS personnel to change the route by which the units were to be accessed as well as which units were to be harvested. The number of runs made to develop alternatives via this approach varied from two to nine.

Simulation with Minimization of Road Cost (MC).—The final harvesting alternatives selected in the variable-access simulation were used in this approach. These selections were specified ("hardwired") in the optimization model, which was then used to minimize discounted total transportation cost. In essence, the IRPM models were operated as if they were TRANSHIP models minimizing network costs (Kirby and others 1981a). In addition to selecting the road construction and reconstruction projects for accessing the specified timber management activities, the solution process calculated DNR, costs, sediment, and so on, based on the specified timber projects and selected road projects.

Table 1.—Management objectives (constraints) used in applying each of the four analytical approaches by series and test area

Test area	Series I	Series II			
	Adjacency	Adjacency	Water[1]	Sediment[1]	Cover/forage[2]
Twin Rocks	Adjacent units could not be harvested within TP1 and TP2, or within TP3	Same as Series I	Initial increase $\leq 8\%$	Not used	Not used
Copeland Creek	Adjacent units could not be harvested within TP1 and TP2, or within TP3	Same as Series I	Average annual increase $\leq 20\%$	Average annual increase $\leq 80\%$	Not used
Pot Mountain	Adjacent units could not be harvested within TP1 and TP2, or within TP3	Same as Series I	Not used	Average annual increase $\leq 48\%$	Cover, summer range $\geq 43\%$ Cover, winter range $\geq 23\%$

[1] Applied separately by drainage.

[2] Applied separately by wildlife management area.

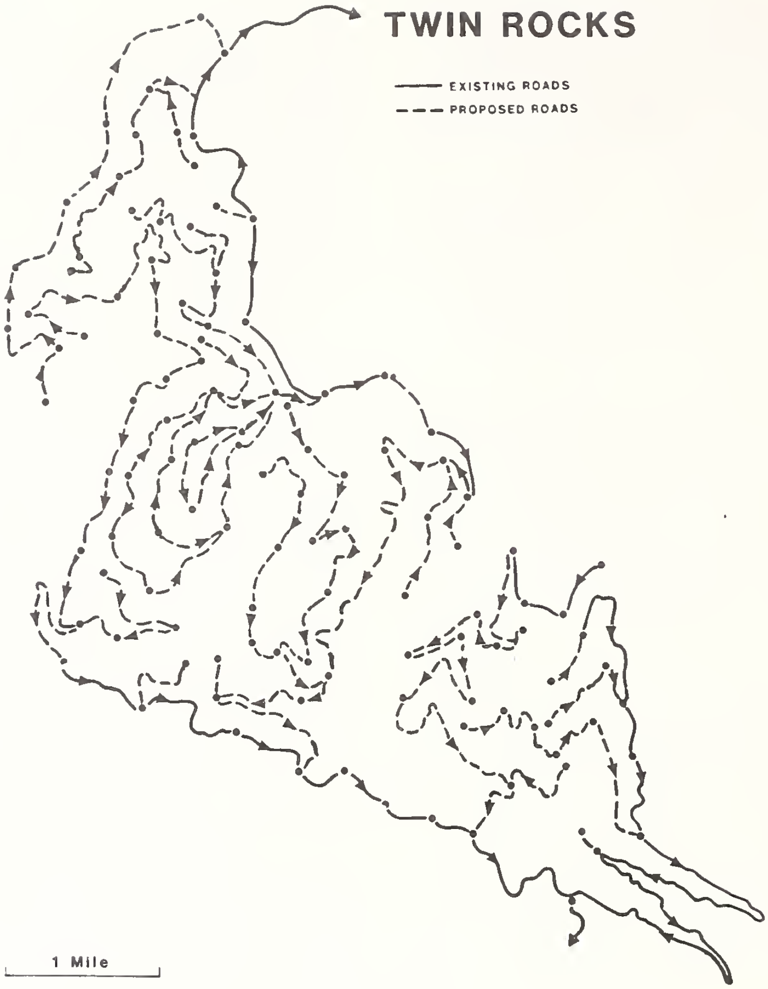


Figure 8.—Fixed-access transportation plan for Twin Rocks.

The TRANSHIP formulation (and IRPM) require solutions in which the road construction projects assume values of 0 or 1.0 (recall fractional values would give rise to a meaningless discontinuous transportation system). One option for attaining such solutions is using a mixed-integer programming (MIP) algorithm. This is feasible, though, with only very small models, say, less than 50 to 100 integer variables. The size of the models to be optimized in this study (smallest contained about 2,000 rows and columns and about 400 integer variables) made using MIP algorithms cost-prohibitive. Instead, a heuristic procedure, which takes advantage of the type of MIP problem developed by IRPM, was used to attain MIP solutions. The heuristic procedure does not produce truly optimal MIP solutions, but is thought to provide good solutions for these formulations. (See USDA Forest Service 1983 for a more complete description of the heuristic procedure.)

Optimization (MX).—For this approach, the optimization model was run as it was designed to operate. The objective function maximized was DNR. The heuristic process used to attain MIP solutions in the MC approach was also used for the MX solutions. The adjacency rule and Series II objectives listed in table 1 were included as constraints. The solution process simultaneously selected timber management activities and road projects (subject to the constraints) while calculating the resulting costs, sediment, and other factors.

RESULTS AND DISCUSSION

An area plan developed by one of the four approaches is shown in figure 9. In this alternative for the Twin Rocks area about three-fourths of the units are scheduled for harvest in the three time periods. Proposed road links scheduled for construction and existing roads scheduled for reconstruction are identified by the time periods (written next to the links) which signify proposed timing for construction. Only a portion of the network presented earlier (fig. 2) is proposed for construction in the 50-year planning horizon.

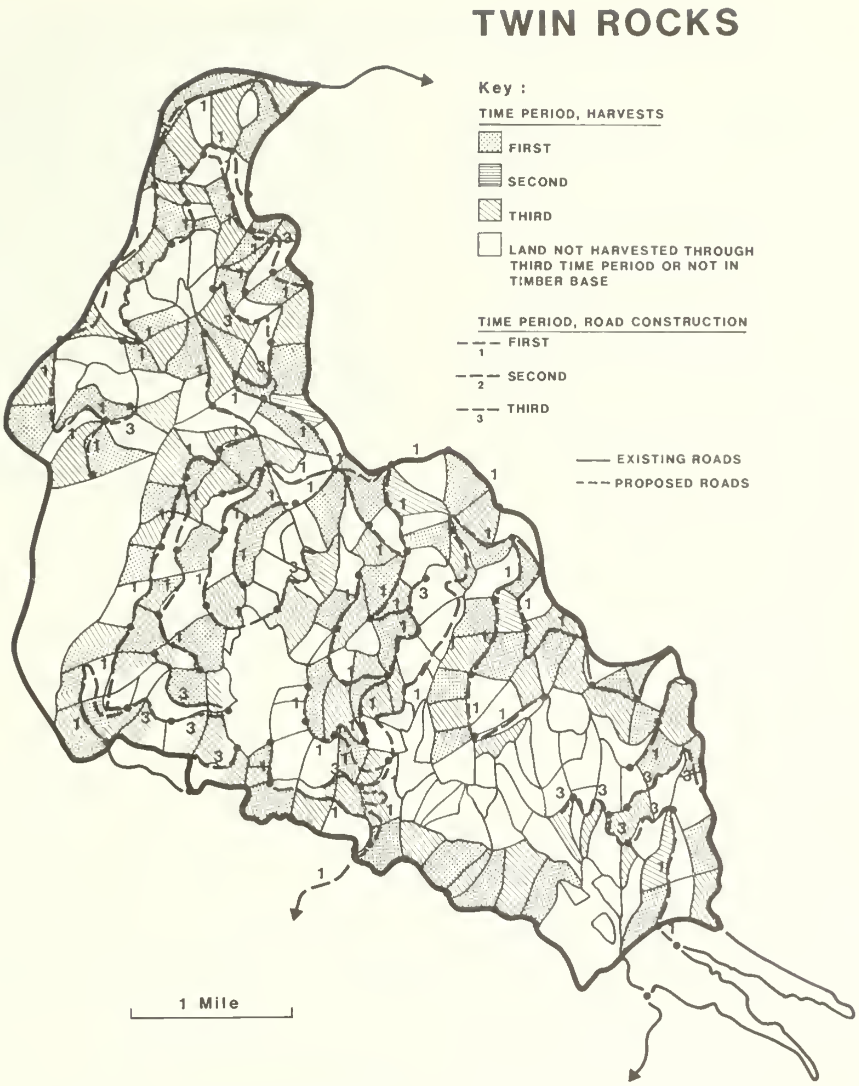


Figure 9.—An example alternative for Twin Rocks.

Plotting results as shown in figure 9 provide analysts and managers with a geographic representation of an alternative. But such plots provide little information for comparing approaches. For this purpose it is more meaningful to look at various statistics calculated from plans developed by the approaches: DNR, miles of road to be constructed, volume of timber to be harvested, and so on.

DNR Comparisons

The DNR's developed via each approach are presented in figure 10. Here, DNR is presented on a per-acre basis (total DNR divided by the total number of acres for which there are potential harvesting activities) to facilitate comparisons across the test areas, which varied greatly in size. The percentages at the top of the bar graphs express DNR for each approach as a percentage of the DNR for the MX approach.

The most striking aspect of figure 10 is the amount by which DNR for the MX approach exceeds those for the other approaches. For the Twin Rocks area the MX approach has a DNR that is $70 per acre greater than the MC approach (highest DNR of the first three approaches) in Series I, and $91 more in Series II. For the Copeland Creek and Pot Mountain areas, the dollar differences between the MX and other approaches are larger. The difference in DNR per acre between MC and MX is $141 for Copeland Creek Series II, and $134 for Pot Mountain Series II. Yet the percentage differences in DNR between each of the first three approaches (FX, VR, and MC) and the MX approach were smaller for Copeland Creek and Pot Mountain than for Twin Rocks.

Differences within the first three approaches were smaller. In fact, there were essentially no differences in the DNR's per acre calculated for the FX, VR, and MC approaches on either Copeland Creek or Pot Mountain. On the Twin Rocks area, DNR for the VR approach exceeded the FX approach by $24 per acre in both Series I and II. The increase between MC and VR was less at $8 per acre for Series I and $6 per acre for Series II.

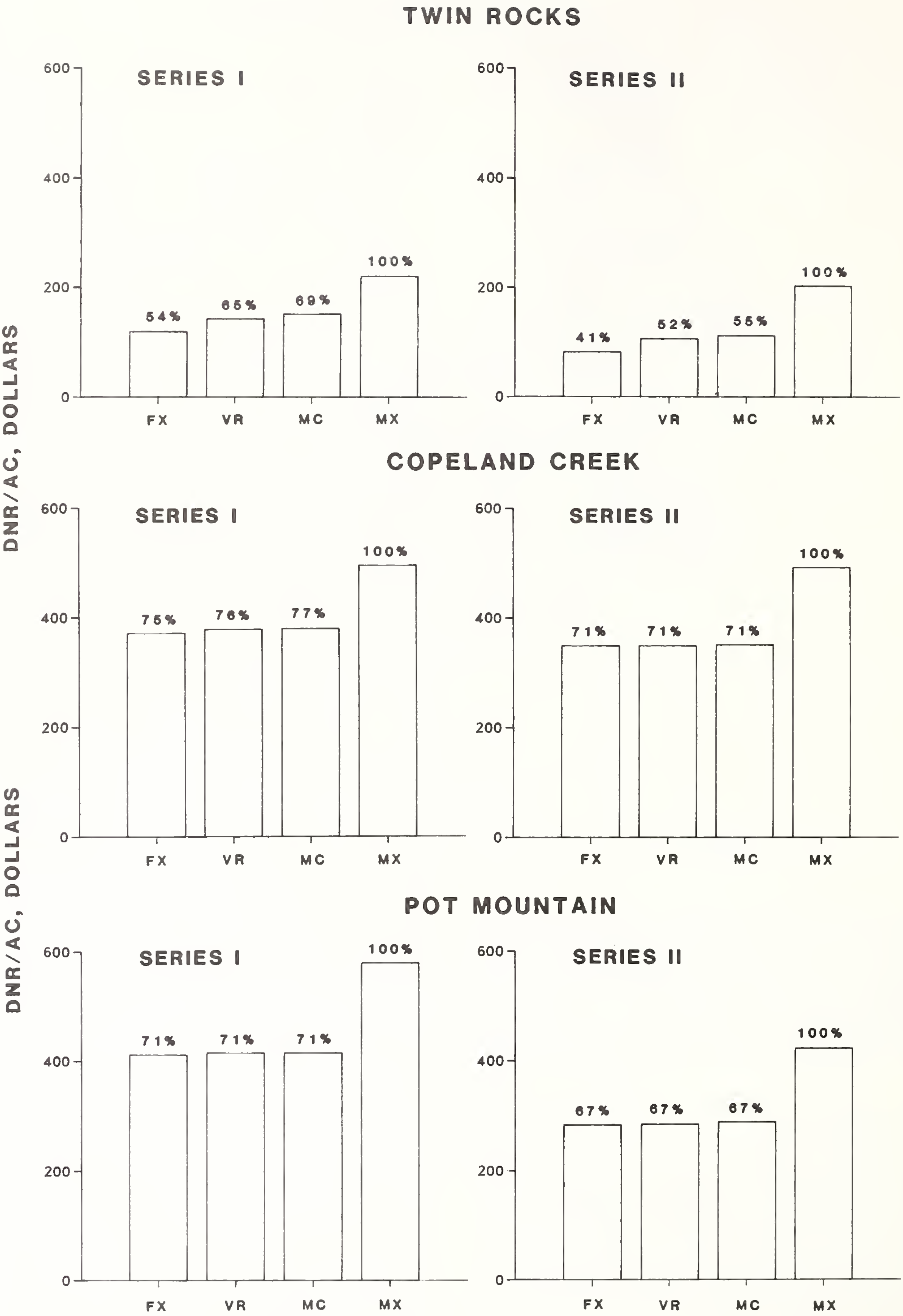


Figure 10.—Average DNR per acre from each approach by series and test area.

A two-way analysis of variance was performed to test for significance in the differences in DNR (fig. 11). It was hypothesized that the analysis technique and test area both influence DNR. The F-values indicate that there are statistically significant differences (95 percent confidence level) in DNR among the approaches and the test areas themselves. The confidence intervals for the DNR means presented in figure 11 indicate where those differences are located. The DNR's calculated for the MX approach are significantly higher than the DNR's associated with the other three approaches (significant differences are indicated when the confidence intervals do not overlap). There are, however, no significant differences indicated among the FX, VR, and MC approaches. Finally, the DNR's associated with the Twin Rocks area are significantly lower than the other two test areas.

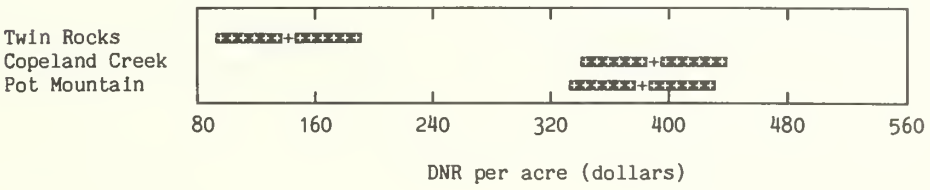
The results presented in figure 10 indicate that the MX approach can be expected to provide area plans with significantly higher DNR's than the other approaches. Next, it was hypothesized that these differences are greater the more complex the planning problem. This hypothesis was tested by performing an analysis of variance on the percentage of the MX DNR achieved by the FX, VR, and MC approaches. Complexity was measured in two ways. First, the Series II planning problems are more complex than the Series I problems because they include sediment, water, and cover/forage objectives as well as the adjacency rule present in both series. Second, complexity varied across test areas. The Twin Rocks area had a more complex transportation aspect due to its grid-shaped network.

ANALYSIS OF VARIANCE

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F-Statistics
Area	2	331,925	165,962	48.8*
Approach	3	70,636	23,545	6.9*
Interaction	6	3,188	531	.2
Error	12	40,778	3,398	
Total	23	446,527		

*Statistically significant at the 95 percent confidence level

95 Percent confidence intervals
for the area means



95 Percent confidence intervals
for the approach means

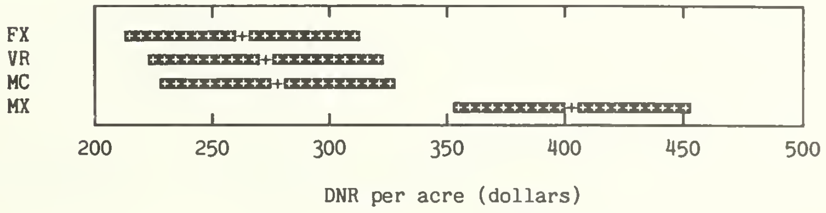


Figure 11.—Statistical test for differences in average DNR per acre across area and approach.

The results of this analysis of variance are presented in figure 12. The F-values for both area and series indicate significant differences at the 95 percent confidence level. The confidence intervals around the area means indicate that the percentage of the MX DNR achieved by the other three approaches was significantly lower for the more complex Twin Rocks area than the other areas. Second, the confidence intervals around the series means indicate that the percentage of the MX DNR achieved by the other three approaches is less for the more complex Series II planning problems. These results support the hypothesis that the more complex the planning problem the greater the differences in DNR between the MX approach and the other three approaches.

Differences in Other Factors

Amounts predicted for other factors help explain the differences observed in DNR and are also of interest in their own right. These factors will be discussed for each test area.

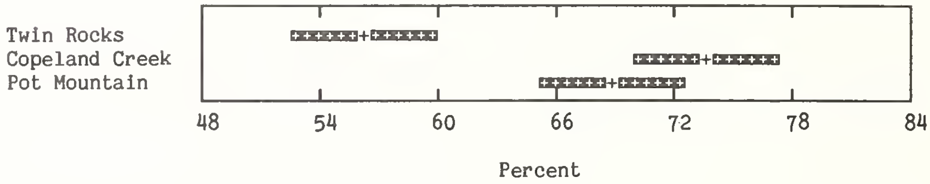
Twin Rocks Area.—Figure 13 presents a number of items for the Series I alternatives. First, consider the alternatives developed by the FX, VR, and MC approaches. The harvest quantities are the same for each of these alternatives. In fact, the same units were selected for harvest in each. Therefore, the differences in transportation-related costs account for the entire differences in DNR across these alternatives. Miles of new road to be constructed in time period 1 decrease as one

ANALYSIS OF VARIANCE

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F-Statistics
Area	2	1,010.5	505.3	26.0*
Series	1	252.4	252.4	13.0*
Interaction	2	83.1	41.5	2.1
Error	12	232.5	19.4	
Total	17	1,578.5		

*Statistically significant at the 95 percent confidence level

95 Percent confidence intervals for the area means



95 Percent confidence intervals for the series means

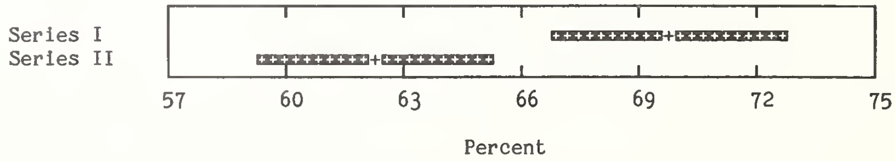


Figure 12.—Statistical test for differences in the percentage of the MX alternatives achieved by the FX, VR, and MC alternatives across area and series.

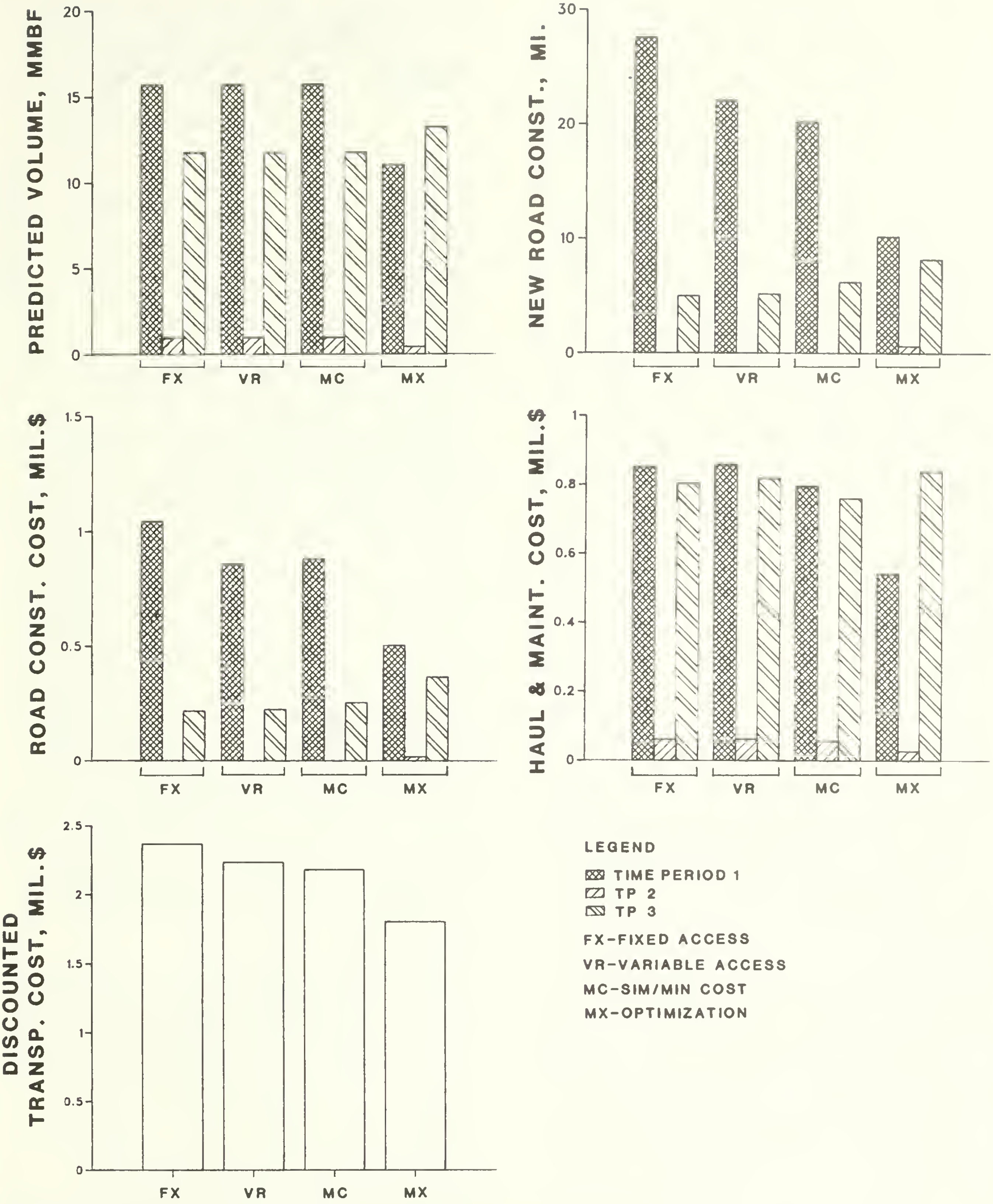


Figure 13.—Items of interest for the Twin Rocks Series I alternatives. (Time period 3 is presented on an averaged decade basis.)

goes from the FX to the VR to the MC alternative. But the reduction in number of miles of new road construction is not the entire story. In time period 1, road construction cost is less for VR than for FX, but the VR haul cost is higher. The net result is a lower total transportation cost in time period 1 for VR. In time period 3, both road construction cost and haul cost are higher for VR. The net result is a discounted total cost for VR that is about $131,000 less than FX.

In the VR and MC approaches trade-offs in haul and construction costs were also made between time periods. Even though fewer miles of road would be constructed in time period 1, construction cost is $25,000 higher for the MC alternative. This increase is offset by lower haul costs, resulting in a total transportation cost for the MC alternative that is $37,000 less in time period 1. The same pattern of higher construction costs but lower haul costs for the MC alternative also occurred in time period 3. The net result was a discounted total cost for MC that is about $57,000 less than the discounted cost for VR.

An important difference between the MX alternative and the other approaches is the quantity of timber to be harvested. The MX alternative would harvest about 5 million bd ft less in time period 1 and about 2 million bd ft per decade more in time period 3. Also, different units were selected for harvest.

There were major differences in the transportation aspect of the Series I MX alternative as well. It would construct substantially fewer miles of road in time period 1, with an accompanying lower overall transportation cost. Then, in the third time period it would construct more miles of road, incurring a higher construction cost.

Much of the difference in DNR between the Series I MX alternative and the other approaches is due to its lower overall discounted total transportation costs. Comparing the MX and MC alternatives illustrates this. DNR for the MX alternative exceeds the MC alternative by $409,000. Of this difference, 92 percent is due to the $378,000 lower discounted total transportation cost of the MX alternative. This lower discounted transportation cost is due to the selection and timing of units to be harvested, as well as transportation selections within the network itself.

The relative levels of harvest and road construction across the four approaches were about the same in Series II (fig. 14) as in Series I. In Series II the same harvest units were selected in the FX, VR, and MC alternatives, so that the differences in DNR among them are due to differences in transportation costs. Also, the MX approach again indicated less timber harvest and road construction in time period 1 and more in time period 3. It is interesting that a smaller percentage of the increase in DNR in the MX alternative relative to the other alternatives is due to a smaller discounted transportation cost for the MX alternative. In this series the difference in DNR between the MX and MC alternatives is $543,000, while the difference in discounted transportation cost is $351,000. The reduction in transportation cost represents only 65 percent of the increase in DNR (as opposed to 92 percent in Series I). In other words, in Series II, selecting units with higher net values represents a greater proportion of the increase in DNR than in Series I, where selecting units which held down transportation cost was more important.

Table 2.—Indicated net stumpage values for Twin Rocks by analysis approach, time period, and series

Series and time period	Analysis approach			
	FX	VR	MC	MX
	Thousands of dollars			
Series I				
Time period 1	−330	−148	−111	440
Time period 2	88	87	94	27
Time period 3[1]	1,692	1,692	1,698	1,702
Series II				
Time period 1	−289	−107	−96	520
Time period 2	52	52	55	34
Time period 3	1,294	1,283	1,312	1,391

[1] Time period 3 presented on an averaged decade basis.

Indicated net stumpage values for the Twin Rocks alternatives are presented in table 2. Indicated net stumpage values differ from DNR in two ways: (1) agency costs for sale preparation and administration and silvicultural exams are not included, and (2) they are undiscounted. Net stumpage value compares the estimated value of timber to the costs that value must cover for timber to sell, assuming all roads are to be financed with purchaser road credits. In other words, it measures the sale viability of the activities within each time period.

The FX, VR, and MC alternatives all have negative indicated net stumpage values in the first time period in both Series I and II. This indicates that some of the roads to be constructed in time period 1 would have to be financed with capital investment (budgeted) dollars. More precisely, the time period 1 activities for one of these alternatives could be packaged as one sale or several sales, but regardless, some capital investment dollars would be required for all the time period 1 activities to be accomplished. The positive indicated net stumpage values for the MX Series I and II alternatives, and time periods 2 and 3 for the FX, VR, and MC alternatives, indicate the activities in those time periods can be accomplished without financing roads with budgeted dollars.

Copeland Creek Area.—The Series I results for Copeland Creek are presented in figure 15. Each of the approaches recognized that, given the assumed growth rates for timber and the real changes in prices and costs, it was most efficient to harvest in time periods 2 and 3. As on Twin Rocks, the same units were selected for harvest in the FX, VR, and MC alternatives. Among these alternatives, the miles of road to be constructed decreased from FX to VR to MC in time period 2 and increased in time period 3. The road construction costs have about the same percentage change across approaches, indicating the lower costs are not a result of selecting lower cost roads, but rather simply fewer miles for construction. Haul cost was virtually the same for each of these three alternatives. The net result is a discounted total transportation cost difference between FX and VR of $59,000 and between VR and MC of only $6,000.

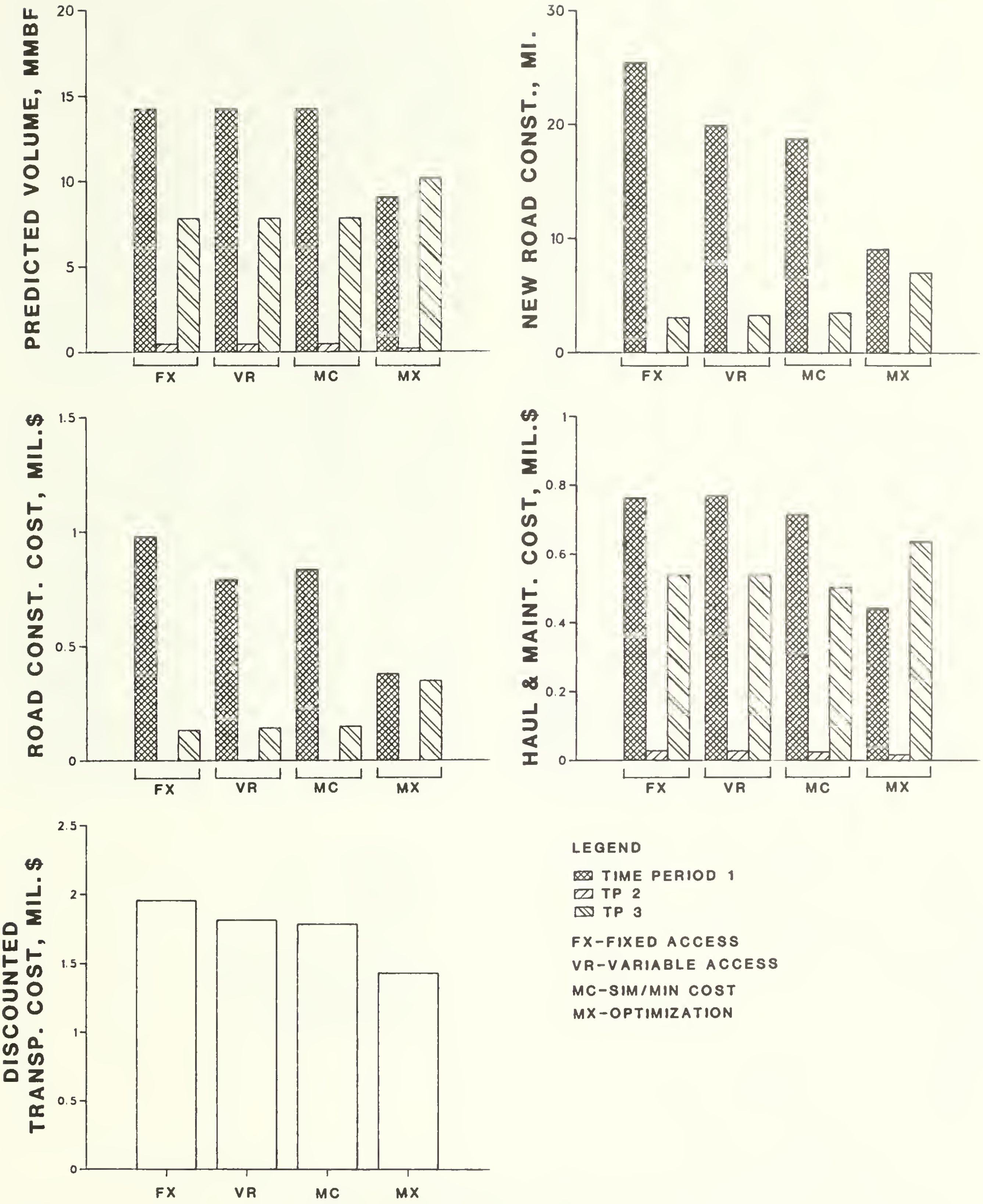


Figure 14.—Items of interest for the Twin Rocks Series II alternatives. (Time period 3 is presented on an averaged decade basis.)

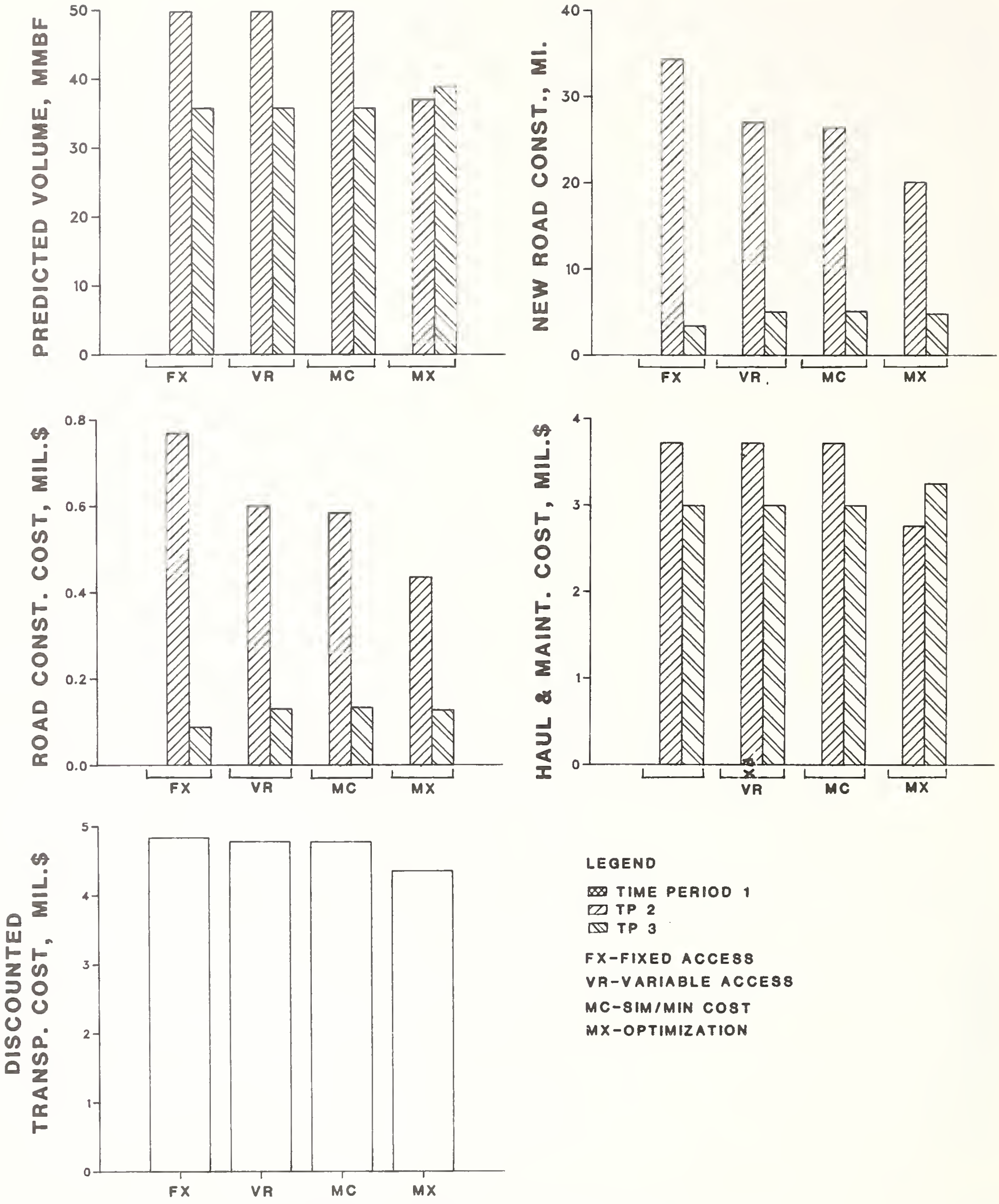


Figure 15.—Items of interest for the Copeland Creek Series I alternatives. (Time period 3 is presented on an averaged decade basis.)

The MX alternative differed from the first three in that it would harvest less timber in the second decade, but more per decade in time period 3. Note, however, that all four alternatives would harvest about the same total quantity over the 50-year planning horizon.

The MX alternative would also construct fewer miles of road in time period 2 than the other approaches and about the same per decade in time period 3. This results in a discounted total transportation cost that is $423,000 less than the MC alternative. This savings accounts for about 42 percent of the difference in DNR between these two alternatives. As for Twin Rocks, this decrease in total transportation cost is due to the selection of units for harvest as well as road construction selections themselves.

In Series II (fig. 16), all four approaches again developed alternatives with harvesting in only time periods 2 and 3. There were no differences in the units selected for harvest among the FX, VR, and MC alternatives and almost no differences in the road links selected for construction. There were some interesting differences regarding the MX alternative, however. Total timber harvest for this alternative is larger in both time periods 2 and 3. As opposed to what was observed in Series I and on Twin Rocks, the MX alternative would construct more miles of road in time period 2 and fewer in time period 3. The road construction costs for MX, relative to the other approaches, reflect these mileage differences. The discounted total transportation cost for the MX alternative is higher than the MC alternative by $382,000. Yet DNR for the MX alternative exceeds the MC alternative by $1.2 million. The MX approach was able to harvest a larger quantity of timber while satisfying the Series II sediment and water objectives.

The indicated net stumpage values (table 3) for the alternatives developed by all four approaches are positive in each time period in both Series I and II. This indicates that the aggregate of the activities within each time period is likely to be financially viable.

Table 3.—Indicated net stumpage values for Copeland Creek by analysis approach, time period, and series

Series and time period	Analysis approach FX	VR	MC	MX
	Thousands of dollars			
Series I				
Time period 1	—	—	—	—
Time period 2	1,149	1,318	1,333	1,270
Time period 3[1]	4,837	4,792	4,789	6,030
Series II				
Time period 1	—	—	—	—
Time period 2	806	806	806	1,253
Time period 3	4,604	4,604	4,621	6,016

[1] Time period 3 presented on an averaged decade basis.

Pot Mountain Area.—The factors for Series I are presented in figure 17. As was the case on Copeland Creek, there were no differences in the units selected for harvest among the FX, VR, and MC alternatives, and very few differences in the road links selected for construction.

Major differences did occur between the MX and other alternatives. The MX alternative would harvest substantially more timber. The greatest increase would occur in time period 2, where the FX, VR, and MC alternatives would harvest only 0.6 million bd ft, while the MX approach would harvest 79.0 million bd ft. The MX alternative also indicated substantially more road construction in time periods 1 and 2 (less in time period 3), with a discounted total transportation cost almost twice that of the other alternatives. The net effect is a DNR for the MX alternative of $15.0 million, versus about $10.8 million for the other alternatives.

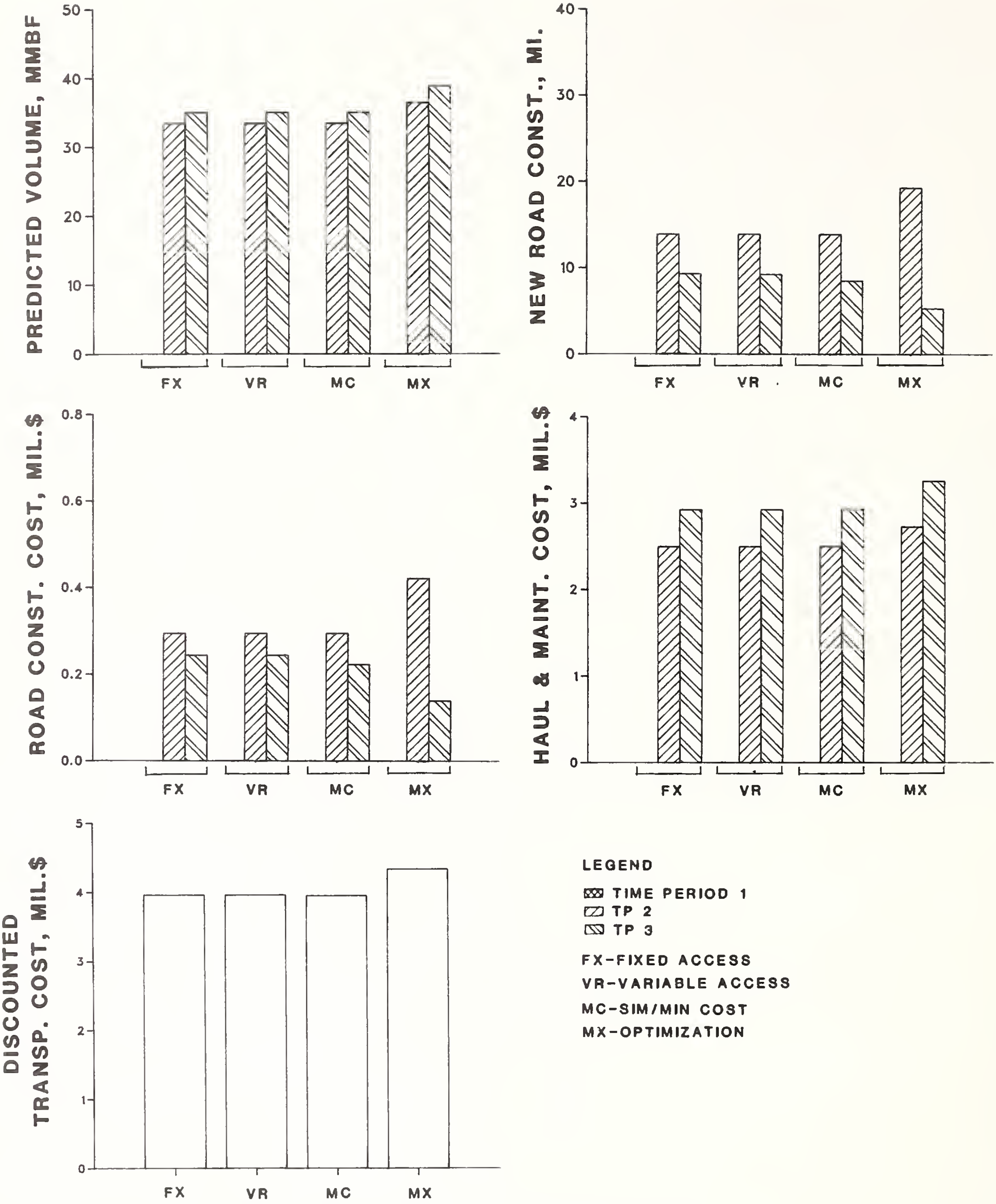


Figure 16.—Items of interest for the Copeland Creek Series II alternatives. (Time period 3 is presented on an averaged decade basis.)

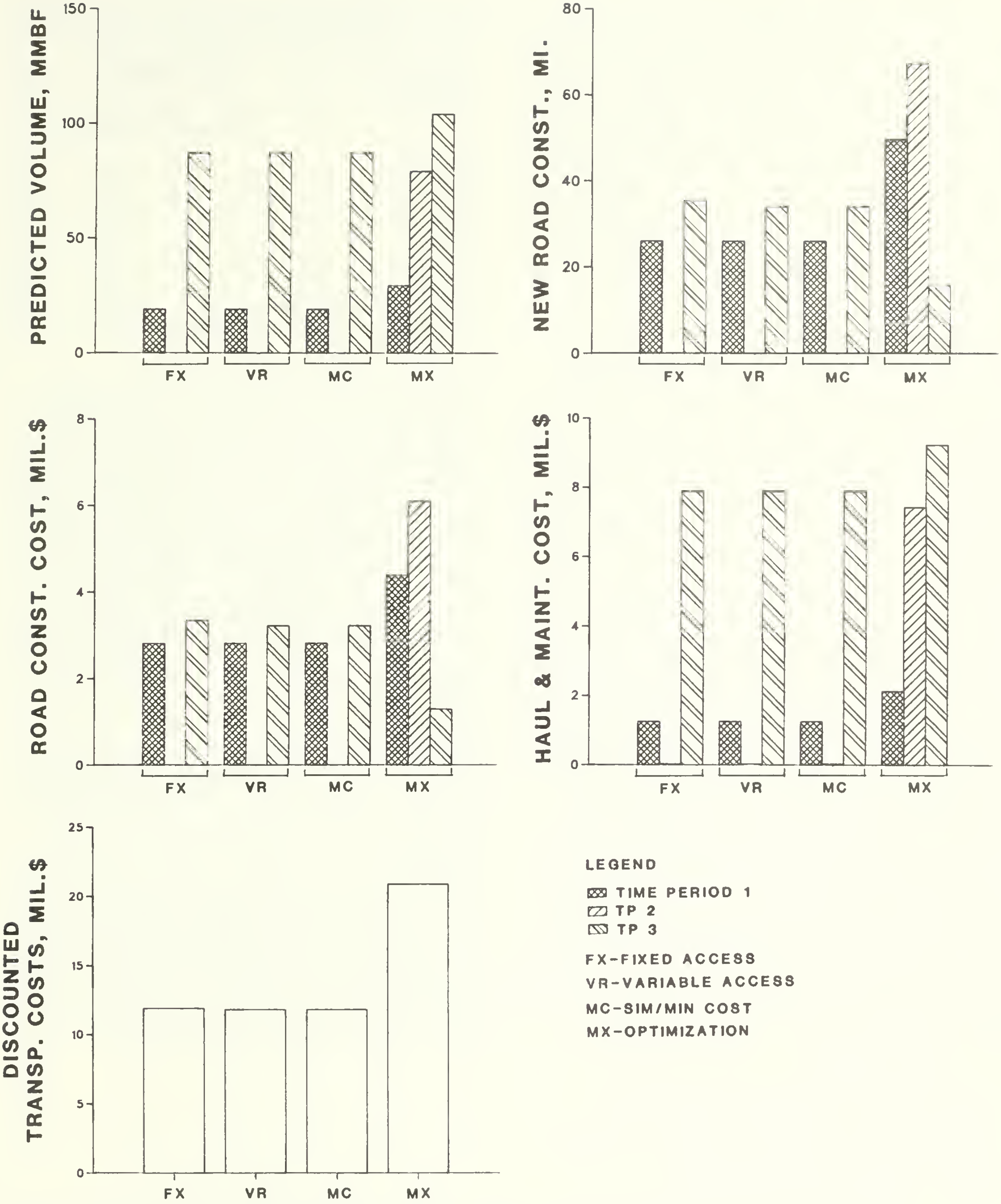


Figure 17.—Items of interest for the Pot Mountain Series I alternatives. (Time period 3 is presented on an averaged decade basis.)

The Series II nontimber objectives for Pot Mountain were substantially more restraining than on the other two test areas. The main route of haul selected for the FX approach could not be constructed into the interior of the Pot Mountain area (where the majority of the current mature timber exists) within one decade. The difficulty was that too much sediment would be created in one of the critical drainages. The solution was to construct this road over two decades, thereby spreading out the impact of sedimentation. As a result, no timber harvests would occur in the FX alternative until time period 2 (fig. 18). Different routes were used in the other alternatives to access the mature timber in time period 1. These routes had somewhat higher costs but satisfied the sediment objectives.

There were some minor differences in the road links selected for construction between the VR and MC alternatives. The latter would construct about a mile less in time period 1, a mile more in time period 2, and 1.5 miles less in time period 3. The net effect was a discounted total transportation cost of $87,000 less for MC, representing the total difference in DNR between these alternatives. Relative to the FX alternative, they had a discounted total transportation cost on the order of $1.3 million more. This higher cost was offset by higher total timber values. DNR for the VR alternative exceeds the FX alternative by $28,000.

The Series II MX alternative would harvest substantially more timber and construct substantially more miles of road than the first three alternatives, while still satisfying the sediment and cover/forage objectives. The major difference in timber harvest would occur in time period 2. Road construction for the MX alternative was somewhat higher in time period 1, substantially higher in time period 2, but less in time period 3. Discounted total transportation cost for the MX alternative is about $5.6 million greater than the VR and MC alternatives and about $7 million greater than the FX alternative. The net effect is a DNR for MX of $10.9 million versus $7.3 to $7.5 million for the other alternatives.

Finally, it is noteworthy that the indicated net stumpage value (table 4) is negative for the first entry in each of the alternatives developed for Pot Mountain. To a large extent, this is due to the amount of road which must be constructed to access the mature timber in this area. Thus, even though the large positive DNR values indicate harvesting in the area is profitable, there is predicted to be a cash-flow deficit in time period 1.

Table 4.—Indicated net stumpage values for Pot Mountain by analysis approach, time period, and series

Series and time period	Analysis approach			
	FX	VR	MC	MX
	Thousands of dollars			
Series I				
Time period 1	−136	−136	−136	−933
Time period 2	42	42	42	4,702
Time period 3[1]	16,646	16,755	16,755	21,726
Series II				
Time period 1	−151	−793	−720	−1,186
Time period 2	−1,037	−152	−239	1,819
Time period 3	12,436	12,714	12,813	17,725

[1] Time period 3 presented on an averaged decade basis.

The Pot Mountain area illustrates a point made in a recent publication dealing with the below-cost timber sale issue (Schuster and Jones 1985). Because of the upfront road construction cost, the activities in the first time period would give rise to a below-cost timber sale if packaged as one sale; that is, the net cash-flow in that time period is negative. Yet, the large positive overall DNR's for the area (for the MX alternatives overall DNR is $15.0 million for Series I and $10.9 million for Series II) indicate the long-run economic returns from timber management are favorable. Eliminating the negative cash-flow in time period 1 by either harvesting more timber in that time period or by postponing harvest until a later time would result in lowering the overall DNR for the area.

Equal Harvest Volume Alternatives.—The overall DNR per acre for the MX alternatives exceeded the DNR's for the other approaches by a substantial margin on each of the three test areas. An obvious question at this point is, "How much of this increase in DNR is due to differences in the quantities harvested across time periods?"

To investigate this question, another MX alternative, called the equal volume MX alternative, was developed for each of the three areas. In these alternatives, the optimization models were required (through constraints) to harvest the same quantities of timber in each time period as the Series II VR and MC alternatives. In addition, the other Series II management objectives listed earlier in table 1 were required to be met as well.

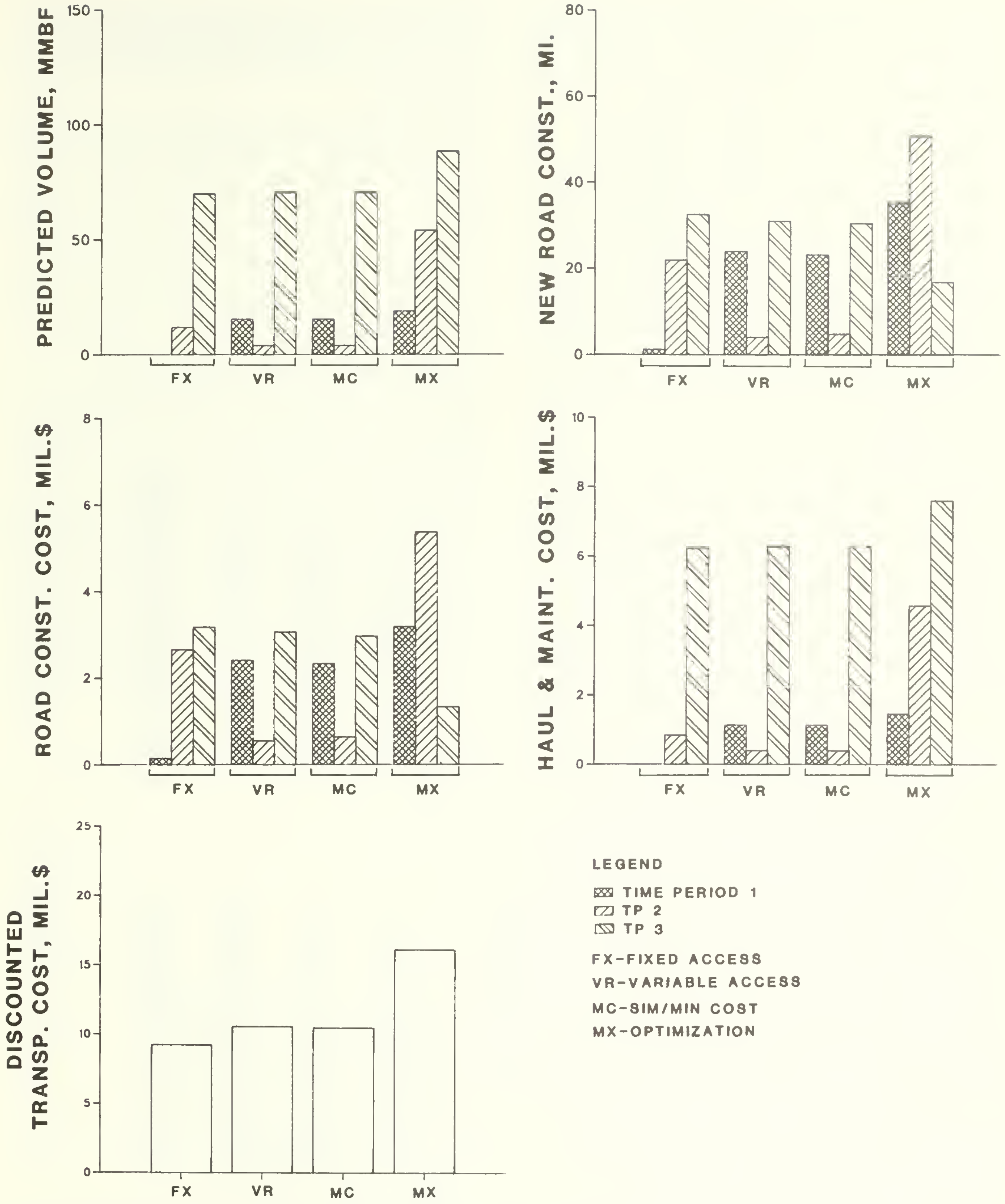


Figure 18.—Items of interest for the Pot Mountain Series II alternatives. (Time period 3 is presented on an averaged decade basis.)

The results from the Twin Rocks equal volume MX alternative are presented along with the Series II results for FX, VR, and MC in figure 19. DNR per acre for the equal volume MX is $177, $26 less than the Series II MX, but still $71 more than the Series II VR alternative.

As was the case for the Series II MX alternative, the new MX alternative would construct fewer miles of new road in time period 1 and slightly more miles in time period 3 than the other three approaches. Largely as a result of fewer miles to construct, road construction cost in time period 1 for the equal volume MX alternative is less than the other approaches. Haul cost for the MX approach is also less. The difference in total transportation cost between the equal volume MX alternative and the other alternatives accounts for 41 percent of the difference in DNR between VR and MX, and 35 percent of the difference in DNR between MC and MX. The balance of the differences in DNR is due to choice of units for harvest to attain the specified levels of harvest in each time period.

For Copeland Creek, DNR per acre for the new MX alternative decreased only $7 from the Series II MX alternative (from $492 per acre to $485 per acre). Road construction mileage and cost are higher in time period 2 for the equal volume MX alternative than the other approaches presented in figure 20, but are lower in time period 3. Haul cost is essentially the same for each of the four alternatives. The resulting difference in discounted total transportation cost between the new MX alternative and the other alternatives accounts for only about 1 percent of the difference in DNR between the new MX and other alternatives. In other words, essentially all of the increase in DNR for the equal volume MX alternative (relative to the other approaches) is due to the units selected for harvest to achieve the same harvest volumes.

DNR per acre for the equal volume MX alternative on Pot Mountain is $338, a decrease of $84 from the Series II MX solution (fig. 21). DNR per acre for the new MX alternative does, however, exceed the Series II VR alternative by $54 and the Series II MC alternative by $50. Miles of new road construction is slightly greater in time period 1 but considerably less in time period 3 for the new MX alternative than the VR or MC alternatives (recall the harvest schedule for the Series II FX alternative was substantially different from the VR and MC alternatives on the Pot Mountain area). Road construction cost for the new MX alternative, however, is slightly less than for VR in time period 1 and is significantly less than both VR and MC in time period 3. In addition, haul cost for the new MX alternative is somewhat less in both time periods 1 and 3. The resulting difference in discounted total transportation cost between the new MX alternative and the Series II VR alternative accounts for 36 percent of the difference in DNR between these alternatives. Thirty-three percent of the difference in DNR between the MX and MC alternatives is explained by the difference in discounted transportation cost between these alternatives. Thus, as was the case on the first two test areas, the majority of the difference in DNR between the equal volume MX alternative and the other approaches can be traced back to the selection of units for harvest to meet the stated harvest objectives.

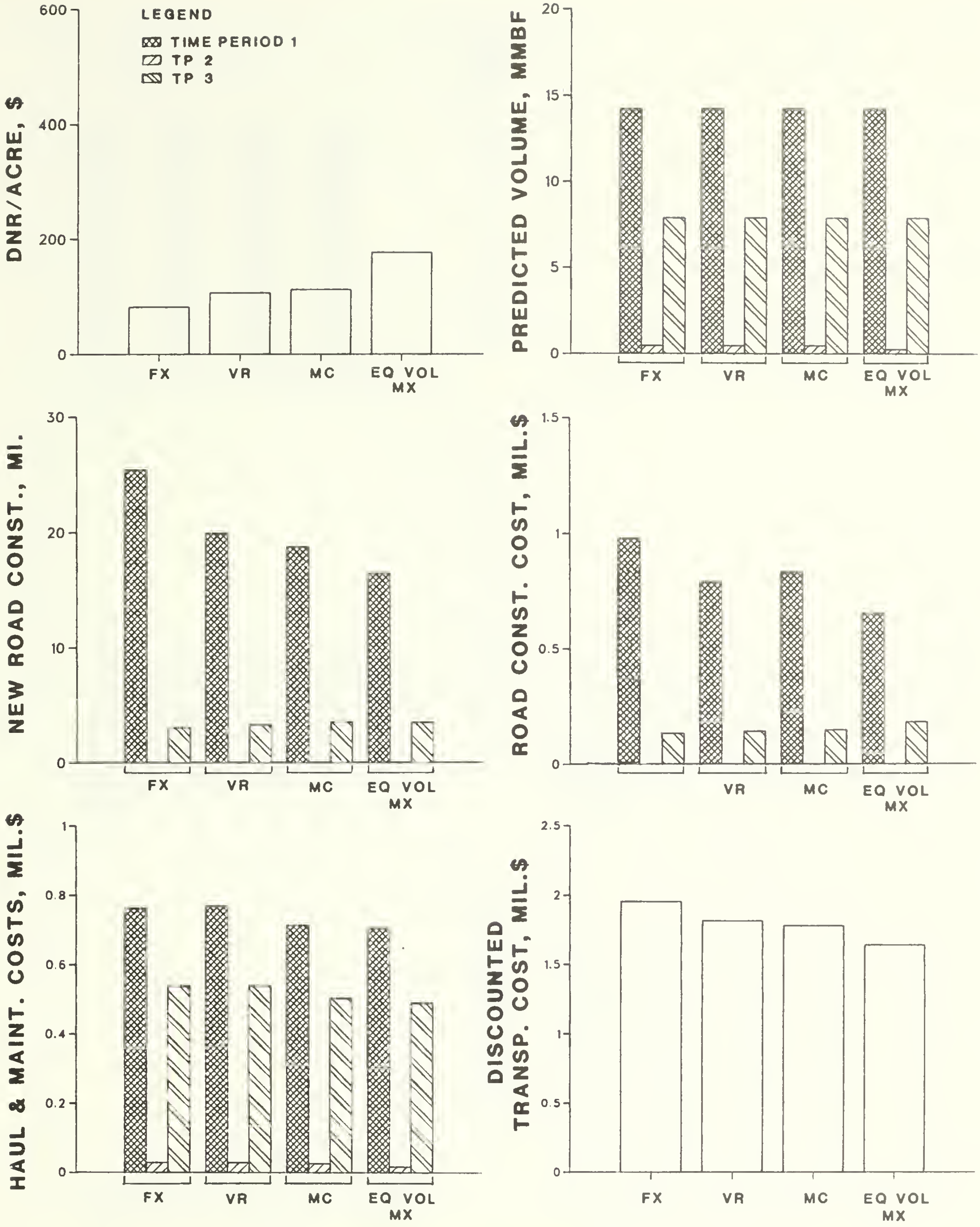


Figure 19.—The equal volume MX alternative compared to the Series II FX, VR, and MC alternatives for Twin Rocks.

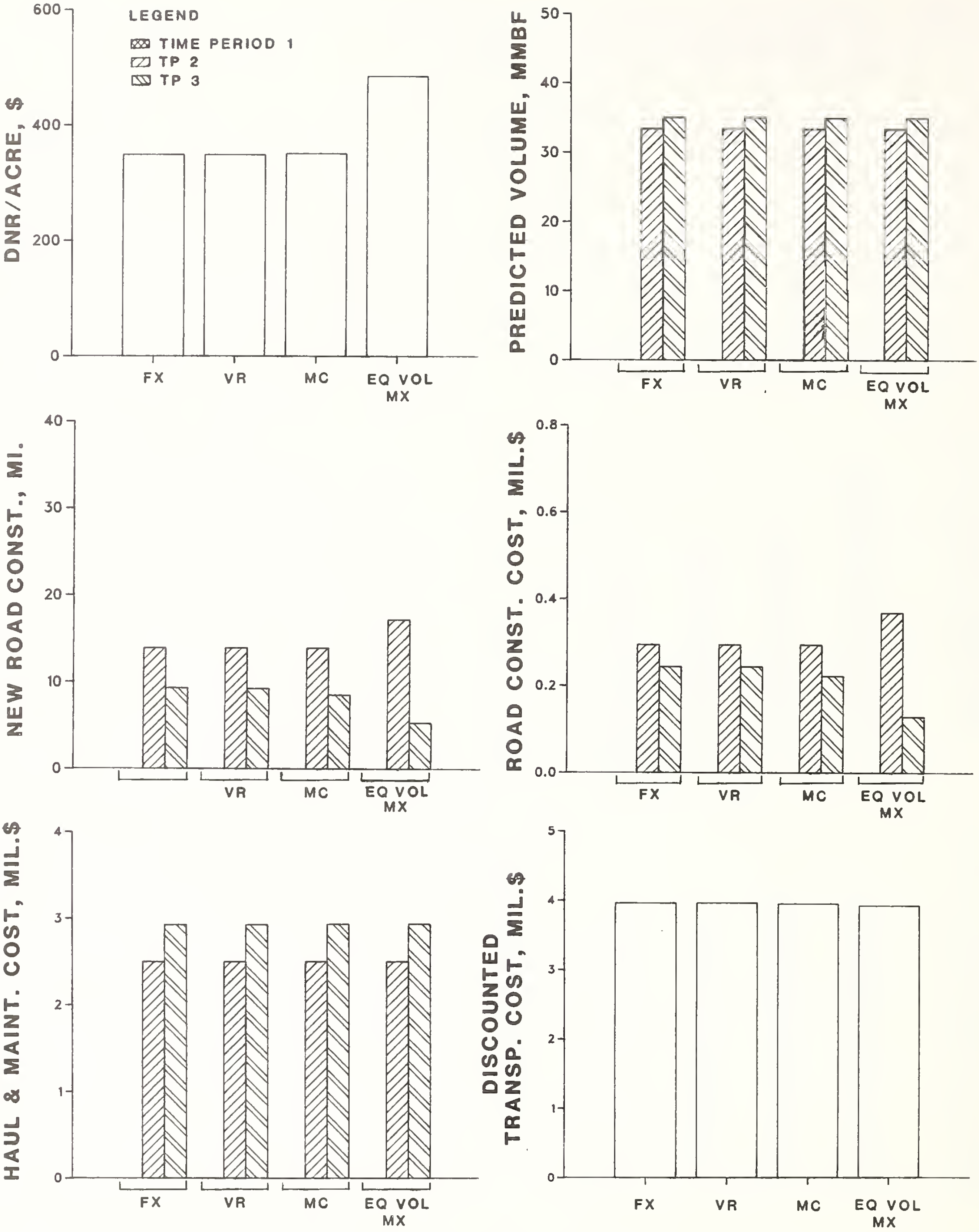


Figure 20.—The equal volume MX alternative compared to the Series II FX, VR, and MC alternatives for Copeland Creek.

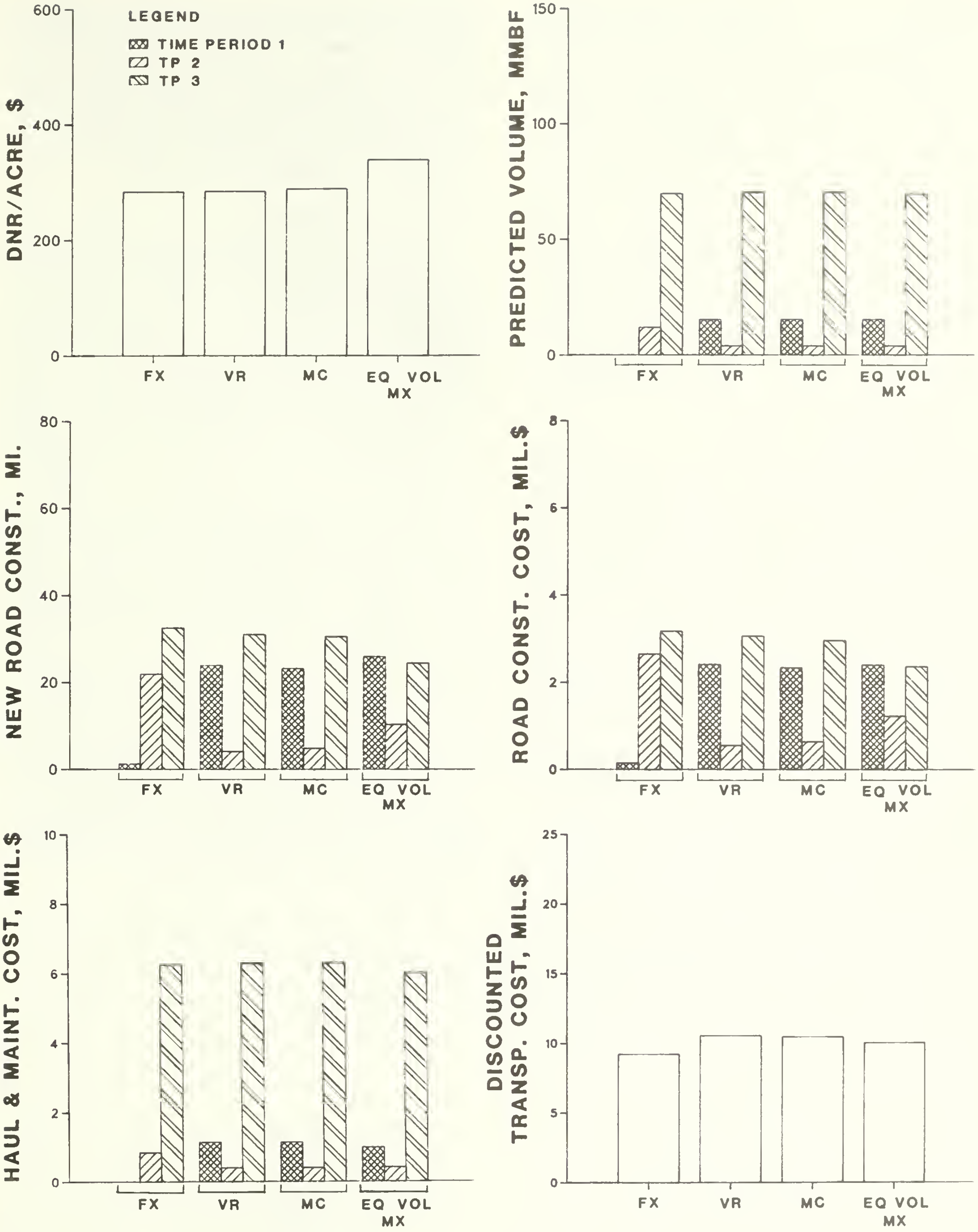


Figure 21.—The equal volume MX alternative compared to the Series II FX, VR, and MC alternatives for Pot Mountain.

The final topic of interest regarding the equal volume MX alternatives is the indicated net stumpage values presented in table 5. For Twin Rocks, the critical indicated net stumpage values are in time period 1 where they were negative for FX, VR, and MC in both Series I and II. Indicated net stumpage for the equal volume MX alternative decreased only slightly from Series II MX (from $520,000 to $483,000). This value exceeds the negative values for FX, VR, and MC by a half million dollars or more.

For Copeland Creek, indicated net stumpage values for all the Series I and II alternatives indicated the activities in each time period can be accomplished without financing roads with budgeted dollars (all indicated net stumpage values were large positive numbers). This trend continued in the equal volume MX alternative, where indicated net stumpage values in both time periods 2 and 3 decreased only slightly from the Series II MX alternative.

Table 5.—Indicated net stumpage value for the equal volume MX alternatives and the Series II FX, VR, and MC alternatives

Area and time period	Analysis approach			
	Series II			Equal volume
	FX	VR	MC	MX
	Thousands of dollars			
Twin Rocks				
Time period 1	−289	−107	−96	483
Time period 2	52	52	55	36
Time period 3[1]	1,294	1,283	1,312	1,275
Copeland Creek				
Time period 1	—	—	—	—
Time period 2	806	806	806	1,173
Time period 3	4,604	4,604	4,621	5,863
Pot Mountain				
Time period 1	−151	−793	−720	−454
Time period 2	−1,037	−152	−239	−491
Time period 3	12,436	12,714	12,813	14,418

[1] Time period 3 presented on an averaged decade basis.

On Pot Mountain, negative indicated net stumpage values were observed in Series II in both time periods 1 and 2 in all alternatives but the MX alternative, which had a positive value in time period 2 (even though each had overall DNR's exceeding $7 million). Relative to Series II MX, indicated net stumpage for the equal volume MX alternative increased from −$1,186,000 to −$454,000, but in time period 2, decreased from +$1,819,000 to −$491,000.

Required Resources

The same data were used for each approach within a test area. Table 6 presents the number of person-days spent supplying data for the test models. Total time is the sum of three categories: network and road projects (which includes developing a log-flow plan); potential harvest units and the associated harvest alternatives; and the yield, cost, and price information. On a per-1,000-acre basis (for areas having harvesting alternatives) number of person-hours ranged from a low of 2.7 for Copeland Creek to 8.1 for Twin Rocks. Several reasons explain at least some of this time difference. Twin Rocks was the first test area. Here, more effort was devoted to deciding what data were needed, how precise the data should be, and so on. For example, the decision to delineate land into operable potential harvesting units was not made until after work on Twin Rocks was begun. In a very real sense, Twin Rocks served as the testing ground for developing the approaches that were applied on the other two areas.

The smaller amount of time devoted to Copeland Creek data is at least partially explained by the fact that a substantial amount of harvesting activity had occurred in the area in the past and about 40 percent of the road network had already been constructed. Also, the relationships for predicting sediment and water yield that had been used on Twin Rocks were modified only slightly for use on Copeland Creek (a totally different approach was used for estimating sediment for Pot Mountain).

Table 6.—Person-days of National Forest System personnel time devoted to supplying data for the test area

	Twin Rocks	Copeland Creek	Pot Mountain
	Person-days		
Network and road construction alternatives	23	10	90
Potential harvest units and alternatives	20	11	40
Yield, cost, and price information	5	2	15
Total time	48	23	145
Time per 1,000 acres with harvest alternatives	8.1	2.7	5.6

In addition to the data preparation task listed in table 6, the MX approach also required identifying the adjacent units for implementing the adjacency rule. In this approach the adjacency rule had to be expressed mathematically, whereas in the other approaches it was implemented by not allowing the cooperating analysts to choose adjacent units. Identifying and recording adjacent units took about 5 person-days each for Twin Rocks and Copeland Creek, and about 12 person-days for the somewhat larger Pot Mountain area.

Once assembled, data were entered into the computer. As stated earlier, IRPM software was used in all four approaches. The IRPM data input process allows for a high degree of flexibility in constructing models, but is extremely labor intensive. Because of this, several computer programs were written that read the data prepared by the cooperating National Forest System personnel and that wrote card images in IRPM format. Once these programs were written and debugged, entering and checking data and generating the linear programming model took about 10 person-days for Twin Rocks and Copeland Creek, and about 15 person-days for Pot Mountain.

It is difficult to predict the resources required for applying each of the four approaches in an operational setting. We have first-hand experience in operating only IRPM and the related software that was used to accomplish each of the four approaches. Second, resource requirements would be expected to depend somewhat on the specific software that would be used for each approach. We can, however, make a few general observations.

First, each of the four approaches requires the same basic data, with one exception—the MX approach, which requires developing mathematical relationships for the adjacency rule described earlier. There is a large range in the quality of data that could be used to conduct ALA, and a corresponding wide range in the cost and time required to prepare those data. The number of person-days reported in table 6 are likely representative of time required for developing data of a similar quality and type for other areas. This includes networks of the type currently used in area transportation planning, delineating an area into potential harvesting units, and developing fairly specific road construction and harvesting activities. Perhaps more time could be profitably spent in developing the yield, cost, and price relationships and data, because once developed the information could be applied over more than one area.

On many National Forests, networks similar to those used in this study are commonly developed in area transportation planning. Thus, applying the approaches described in this study would mainly require additional data for delineating potential harvest units and developing the harvesting alternatives. Portions of the yield, cost, and price information would also require additions to current procedure. But, once developed, these relationships could likely be applied on other areas within a Ranger District with little or no modification.

Significant labor savings may be possible if a data-digitizing system were to be used to enter road link and potential harvest unit data. This would make it possible to calculate electronically such things as length of road links and acreage of potential harvest units. Digitized data would also streamline plotting the geographic location of road construction and harvest activities selected in an alternative for area management.

There are some significant differences in computer resources required among the four approaches. The simulation approaches could conceivably be operated on a microcomputer and certainly on a minicomputer such as the Data General equipment owned by the Forest Service.

The MC approach is somewhat more demanding of processing equipment because of the need to include a routine that minimizes discounted transportation cost. Some of the transportation cost minimization programs operate on large, mainframe computers such as the USDA Fort Collins Computer Center, for example, TRANSHIP (Kirby and others 1981a), Timber Transport Model (Sullivan and Barnes 1980), and MINCOST (Schnelle 1977). But, at least one program, NET4T (Sessions 1985), is reported to operate on small computers.

The MX approach is the most demanding of computer resources of the four approaches. For the near future, it almost certainly would require a mainframe computer system. Cost for developing an alternative using the MX approach on Twin Rocks and Copeland Creek ranged between $35 and $55 (using T priority at the Fort Collins Computer Center). Cost for Pot Mountain was somewhat larger, $140 to $200 per MX alternative, because the model for this area was substantially larger (roughly 6,000 rows and columns versus about 2,000 rows and columns for the Twin Rocks and Copeland Creek models).

CONCLUSIONS

The purpose of this study was to compare four analytical approaches for use in integrated area level analysis. The objective for each approach was to develop the management alternative that has the highest DNR possible, while satisfying the Series I and Series II management objectives. DNR was chosen because it is a good measure of management efficiency (an alternative that gives rise to the highest DNR while satisfying the other management objectives is efficient). It is believed that comparing other possible objectives to be maximized or minimized (timber volume per some specified period of time, discounted total cost) would result in similar relative differences.

Significant differences were found among the alternatives developed using the four approaches. One major difference was that the DNR's associated with the MX alternatives were significantly higher than the DNR's for the alternatives developed by the other three approaches. This difference was statistically significant at the 95 percent confidence level. The average difference in DNR between the MX and MC approaches (MC was the approach with the next highest average DNR) was $119 per acre. This amounts to an average difference in DNR on the order of $1.2 million on an area having 10,000 acres with harvest alternatives in a 50-year planning horizon.

The difference in efficiency between the MX and other approaches appears to be larger the more complex the planning problem. The percentage of the MX DNR achieved by the other approaches was significantly lower (95 percent probability level) for the relatively more complex Series II planning problems than for Series I. Further, the percentage of the MX DNR achieved by the other approaches was significantly lower (95 percent confidence level) for the Twin Rocks area. The Twin Rocks area had a grid-shaped road network, which was more complex from a transportation standpoint than the Copeland Creek and Pot Mountain networks.

There were no statistically significant differences among the DNR's associated with the alternatives developed by the FX, VR, and MC approaches. Differences in DNR for these three approaches are hardly perceptible in figure 10 for Copeland Creek and Pot Mountain. On Twin Rocks, however, the differences in DNR for these three alternatives were somewhat larger. In Series II, the DNR for FX was 41 percent of the MX alternative, while MC was 55 percent, a $30 per acre difference. This suggests that statistically significant differences could exist among these three approaches when the transportation aspect of area-level analysis is complex. Unfortunately, this study did not have a sufficient number of areas to test this hypothesis.

The differences found between the MX and the other approaches were not consistent from one area to the next. On Twin Rocks, the MX alternatives tended to defer more timber harvest and road construction from time period 1 to time period 3 in both Series I and II. The same relative pattern occurred in Series I on Copeland Creek, except here the harvesting and road construction were deferred from time period 2 to time period 3. In Series II, however, the pattern reversed—the MX alternative would harvest more timber and construct more miles of road in time period 2. For Twin Rocks and Copeland Creek, although the timing of harvest varied, each approach within a series would harvest roughly the same quantity of timber over the five-decade planning horizon. In contrast, on Pot Mountain, the MX alternative would harvest substantially more timber and construct substantially more miles of road over the planning horizon.

These differences are the result of differences in timber growth rates, the spatial location of potential roads and harvest units, and differences in costs and delivered log prices and how they are assumed to change over time.

An additional MX alternative was developed for each test area to determine how much of the difference in DNR between the Series II MX alternatives and the other approaches was due to differences in harvest scheduling. For these solutions, the optimization models were forced to harvest the same quantities of timber per time period as the Series II VR and MC approaches, as well as satisfy the other Series II objectives.

Significant differences in DNR per acre were also found between these new MX alternatives and the Series II VR and MC alternatives. These differences averaged $86 per acre between the new MX alternatives and the Series II VR alternatives and $82 between the new MX alternatives and the Series II MC alternatives.

The study provides much less information about the resources required by each of the four approaches, largely because the tests involved generic categories of analysis, not computer software. Several observations can, however, be made:

1. Under the general formulation used in this study (potential harvesting units and proposed road links), each of the four approaches requires essentially the same data. The only difference is the adjacency relationships required for the MX approach. There could, however, be major differences in the ease and efficiency of data entry processes among computer software packages, even within one of our approach categories.
2. Once data are entered, substantially more calculations are made in the MX approach than in the simulation approaches. As a result, the MX approach requires more computer resources and computer expertise among the users. Based on our experience, computer costs could be expected to range from $30 to $250 per area-level analysis alternative. This additional cost could, however, be rather modest when compared to data preparation and entry costs associated with each approach.
3. Resources required for an MC approach could vary considerably, depending on the computer routine used to minimize discounted total transportation cost. Some routines for minimizing transportation cost require a large computer system. For them, the resources required would be expected to be similar to the MX approach. But at least one routine for minimizing transportation cost (Sessions 1985) is reported to operate on small computers. Resources required if this were integrated into an MC system would be expected to be similar to the FX and VR approaches.

In area-level analysis, rational choice among analysis approaches involves a comparison of costs and benefits of each approach. The DNR's associated with the test applications in this study indicate the net timber benefits provided by the approaches. Unfortunately, the study was not able to provide comparable estimates of the resources required for implementing each of these approaches. In view of this fact, comparing these approaches via a break-even analysis based on difference in measured benefit (DNR) would seem appropriate. To illustrate, the average difference in DNR per acre between the MX and MC approaches was $119 per acre, or $1.19 million for a typical 10,000-acre area. This means that up to $1.19 million more could be spent conducting an MX analysis before one would be indifferent in choosing between the MX and MC approaches. If the cost of conducting an MX approach were to exceed the cost of implementing the MC approach by more than $1.19 million, then the MC approach would be preferred. Similar break-even points could be calculated for comparisons among the other approaches.

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U.S. GOVERNMENT PRINTING OFFICE: 1985-0-676-039/20033

Jones, J. Greg; Hyde, James F. C., III; Meacham, Mary L. Four analytical approaches for integrating land management and transportation planning on forest lands. Research Paper INT-361. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 33 p.

Four approaches for analyzing site-specific transportation systems and timber harvesting alternatives on small areas were tested on three planning areas. The approaches ranged from a rather simple simulation to optimization. The same data were used for each approach on an area. The optimization approach resulted in significantly higher discounted net revenues (95 percent confidence level) than plans developed by the other approaches when management objectives were identical.

KEYWORDS: area-level analysis, integrated transportation planning, network analysis, timber management, land management planning

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